

The CUORE experiment: results and perspectives



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Neutrino Seminar Series 2020-2021,
Fermilab - virtual
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- Double beta decay and low temperature detectors
- The CUORE experiment
- CUORE data taking
- Results from CUORE:
 - $0\nu\beta\beta$ decay search
 - $2\nu\beta\beta$ decay measurement and background
 - $0\nu\beta\beta/2\nu\beta\beta$ decay to excited states

What do we know about neutrinos

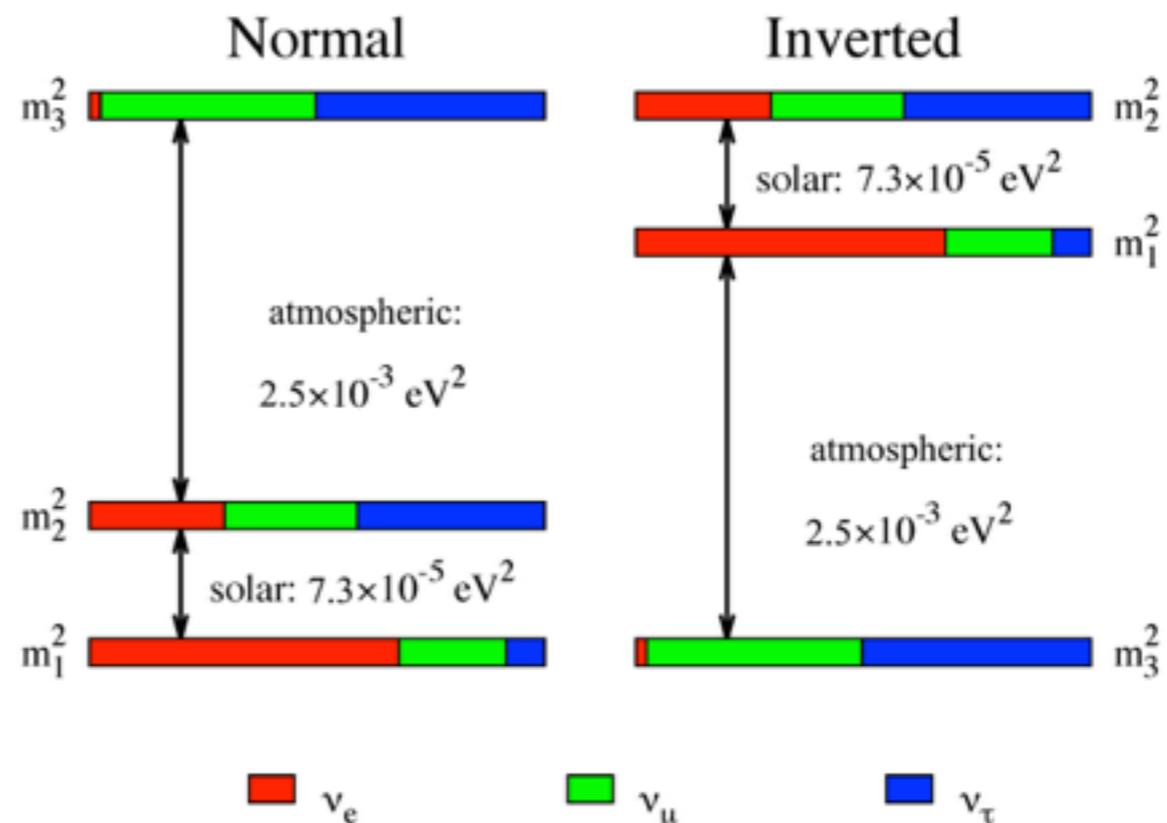
Neutrinos are the least understood particles among the building blocks of the Standard Model

- * Neutrinos are neutral particles, hypothesized by Pauli and Fermi to explain electron energy spectra in weak beta decay
- * Three neutrino flavors appearing in weak interactions
- * Neutrino flavor oscillations: neutrinos have non-zero mass
- * Pontecorvo, Maki, Nakagawa, and Sakata theory for neutrino mass mixing

$$(\nu_e, \nu_\mu, \nu_\tau)$$

$$\nu_l = \sum_{i=1}^3 V_{li} \nu_i \quad (l = e, \mu, \tau)$$

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$



Open questions about neutrinos



- ❖ The Minimal Standard Model (MSM) assumes massless neutrinos; need to extend it to accommodate for massive neutrinos
- ❖ Neutrino mass hierarchy
- ❖ Neutrino mass absolute values. Why neutrino mass is so small?
- ❖ Neutrinos are Dirac or Majorana particles?

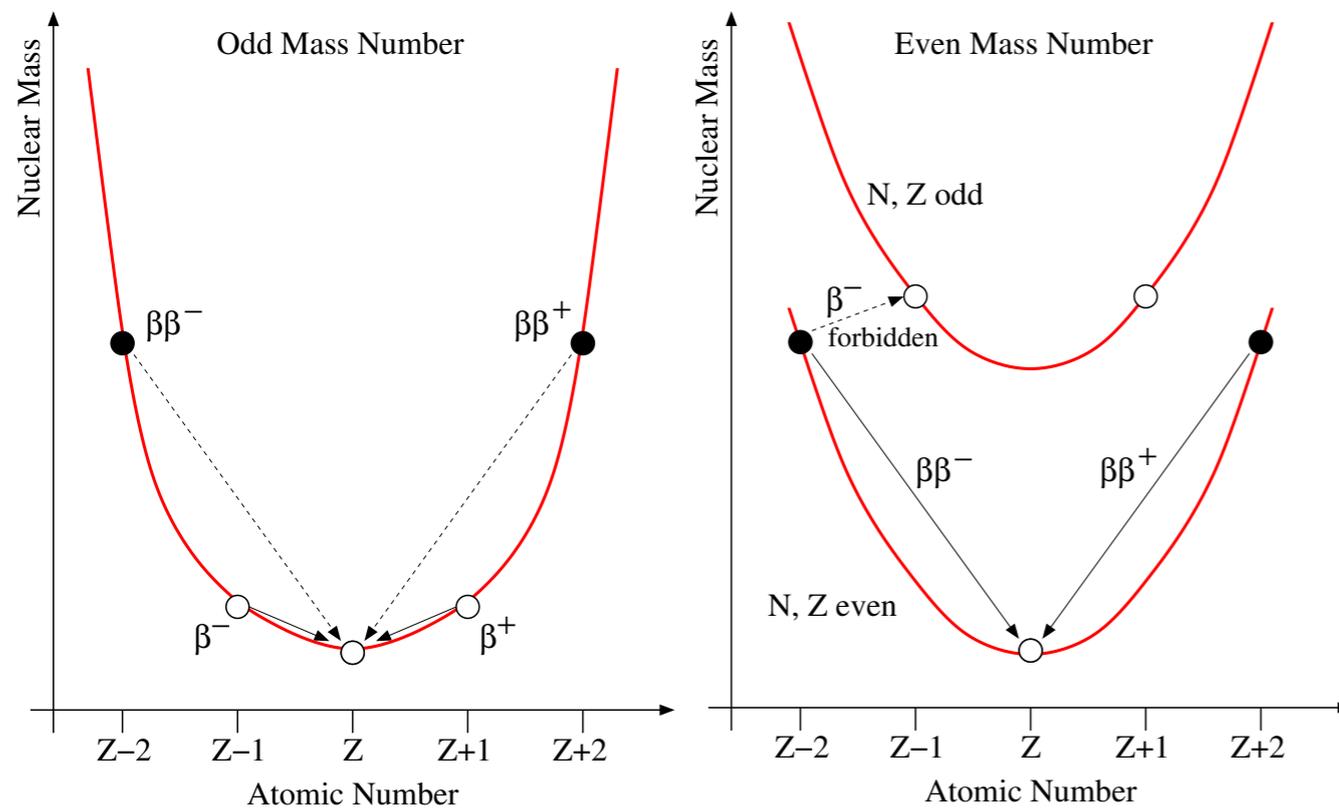
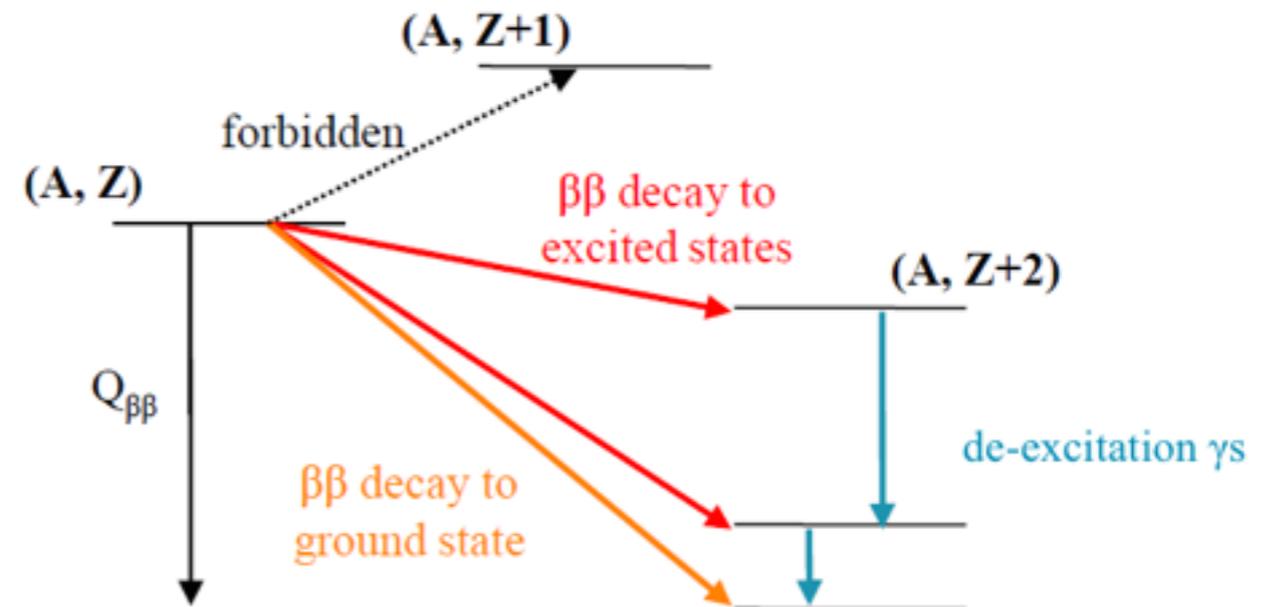
Experimental searches:

- ❖ Neutrino flavor oscillation parameters precision measurement (solar, atmospheric, accelerator and reactor neutrinos): T2K, Nova, Daya-Bay, Super-K,...; DUNE, Hyper-K, JUNO,...
- ❖ Sum of neutrinos masses from cosmological and astrophysical data (mainly CMB and large scale structures): PLANCK,...
- ❖ Direct neutrino mass measurement from β -decay spectral shape: KATRIN (^3H), HOLMES and ECHO (^{163}Ho)
- ❖ Majorana nature of neutrino via neutrinoless double beta decay: CUORE, GERDA, EXO-200, NEMO...; CUPID, LEGEND, Kamland-Zen, SNO+, AMoRE, ...
- ❖ eV-scale sterile neutrino searches: FNAL SBN program (MicroBoone, ICARUS, SBND), PROSPECT, NEOS, DANSS, Neutrino-4, Solid, ...

Neutrinoless double beta decay: unique tool to probe the Majorana nature of neutrino

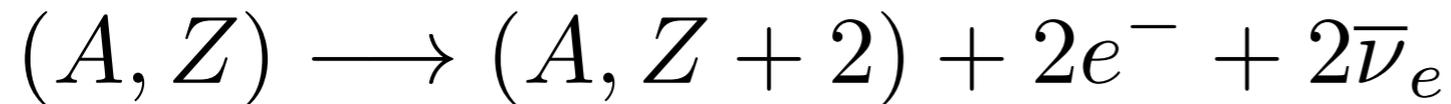
Double beta decay

Double beta decay is a second-order weak decay where a nucleus, (A, Z) undergoes two beta decays to its isobar $(A, Z+2)$ in a single step, emitting two electrons in the process.

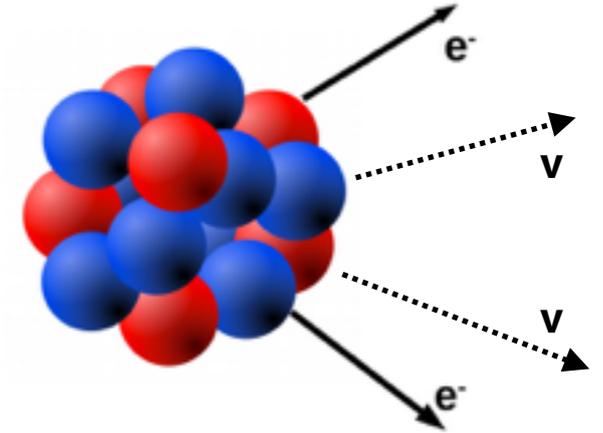


Suitable nuclei for double-beta decay are ^{48}Ca , ^{76}Ge , ^{82}Se , ^{100}Mo , ^{116}Cd , ^{130}Te , ^{128}Te , ^{136}Xe ..., which are all even-even nuclei and the beta transition to the intermediate nucleus is forbidden.

Two neutrino double beta decay ($2\nu\beta\beta$)

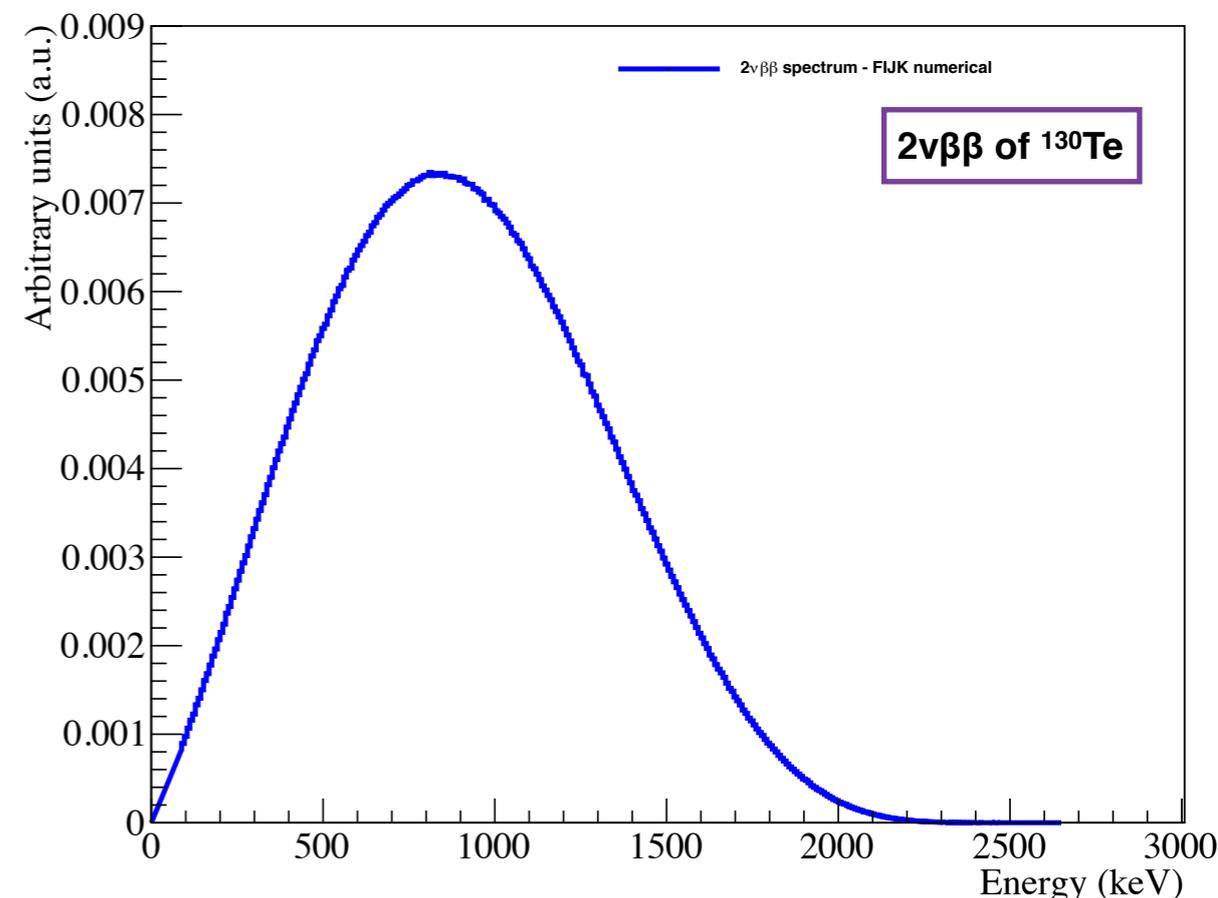


- ◆ 2nd order process allowed in Standard Model ($\Delta L = 0$)
- ◆ Proposed in 1935 by Maria Goeppert-Mayer
- ◆ Observed in several nuclei: $T^{1/2}_{2\nu\beta\beta} \sim 10^{18-24}$ yr



Most relevant measurable quantity:
sum of the kinetic energy of the electrons
produced in the decay - continuous spectrum
with endpoint at $Q_{\beta\beta}$

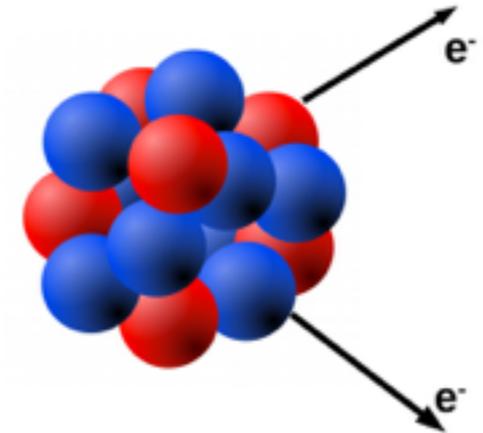
$2\nu\beta\beta$ electrons sum energy spectrum



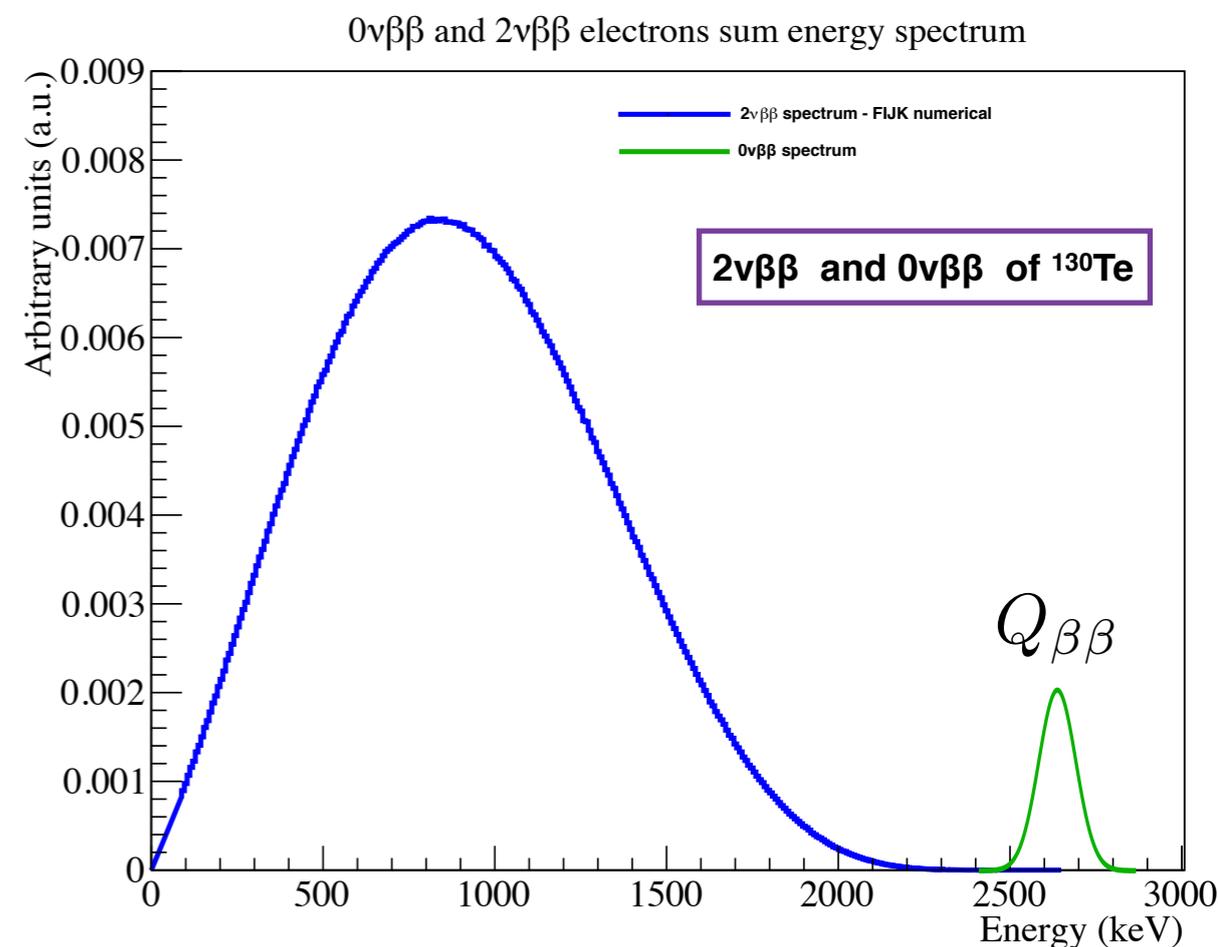
Neutrinoless double beta decay ($0\nu\beta\beta$)

$$(A, Z) \longrightarrow (A, Z + 2) + 2e^{-}$$

- ◆ Beyond Standard Model process: violation of lepton-number ($\Delta L = 2$)
- ◆ Standard Model extension accommodating for a Majorana neutrino nature
- ◆ Not yet observed $T^{1/2}_{0\nu\beta\beta} > 10^{24-26}$ yr



Experimental signature of $0\nu\beta\beta$ decay:
a peak in the summed energy spectrum of
the final state electrons at the Q-value of the
 $\beta\beta$ decay ($Q_{\beta\beta}$)



Neutrinoless double beta decay ($0\nu\beta\beta$)

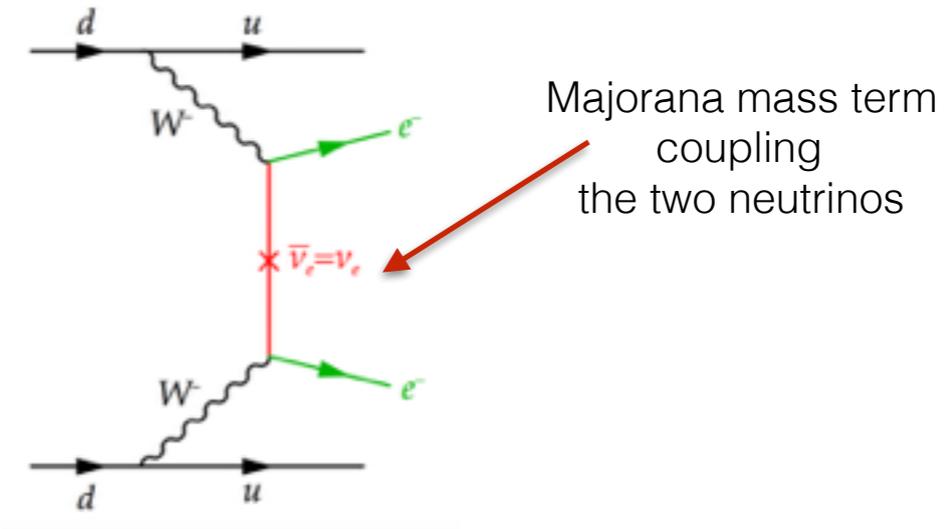
Observation of $0\nu\beta\beta$ decay would imply:

- Lepton number violation
- Presence of a Majorana term for the neutrino mass
- Constraints on neutrino mass hierarchy and scale
- Hint on origin of matter/anti-matter asymmetry

From $0\nu\beta\beta$ decay rate measurements one can infer the effective neutrino mass term

$0\nu\beta\beta$ favorite mechanism:

Light Majorana neutrino exchange



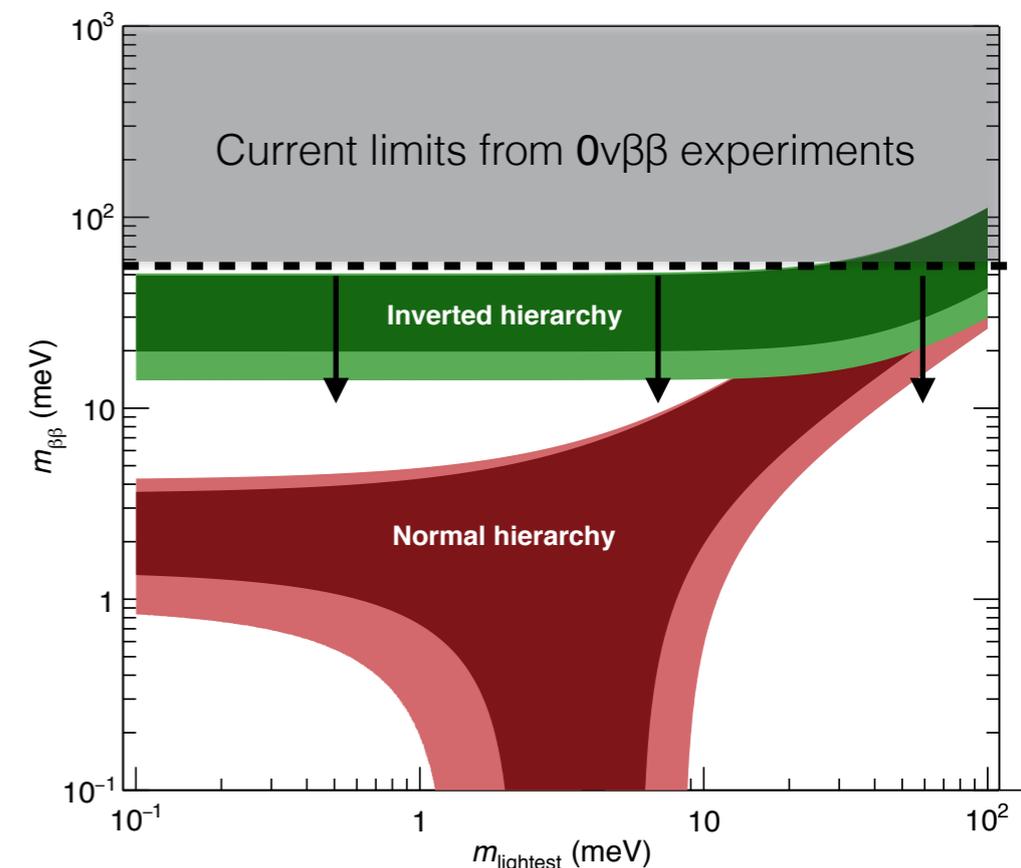
$$\frac{1}{T_{1/2}^{0\nu}} \propto G(Q_{\beta\beta}, Z) |M_{nucl}|^2 |m_{\beta\beta}|^2$$

Phase space integral

Nuclear matrix element (NME)

Effective neutrino mass term

$$m_{\beta\beta} \equiv \left| \sum_i m_{\nu_i} U_{ei}^2 \right| = \left| e^{i\alpha_1} |U_{e1}^2| m_1 + e^{i\alpha_2} |U_{e2}^2| m_2 + |U_{e3}^2| m_3 \right|$$



Experimental $0\nu\beta\beta$ sensitivity

The number of observable $0\nu\beta\beta$ decays is limited by the fluctuations of the background counts around $Q_{\beta\beta}$ (region of interest, ROI)

‘Finite background’

$$S_{0\nu} \propto \eta \cdot \epsilon \cdot \sqrt{\frac{M \cdot T}{\Delta \cdot B}}$$

‘Zero background’ ($B \cdot \Delta \cdot M \cdot T \ll 1$)

$$S_{0\nu} \propto \eta \cdot \epsilon \cdot M \cdot T$$

Isotope choice

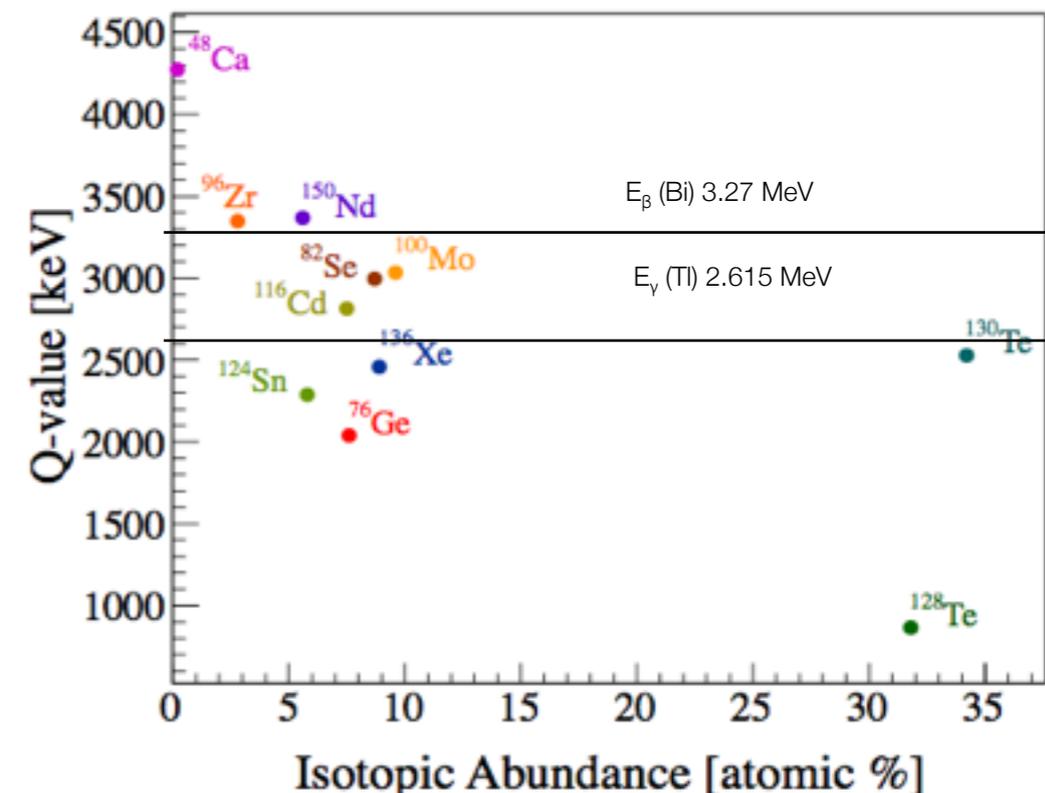
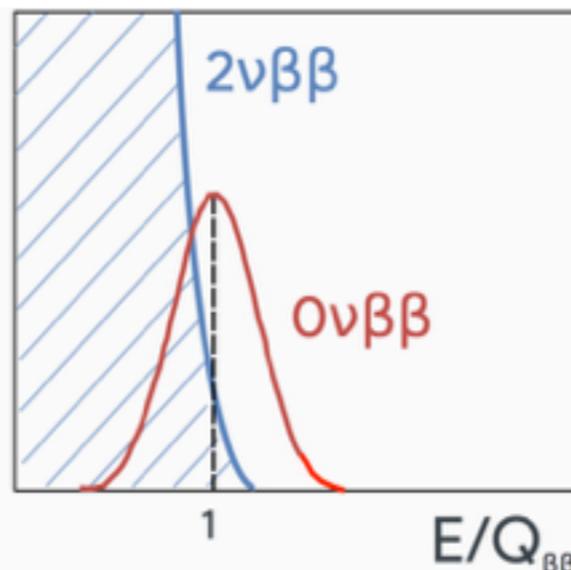
- High isotopic natural abundance or enrichment, η
- High Q-value, $Q_{\beta\beta}$

Detection technology

- Good detection efficiency (ϵ): $\beta\beta$ source embedded into the absorber
- Excellent energy resolution (Δ)

Exposure

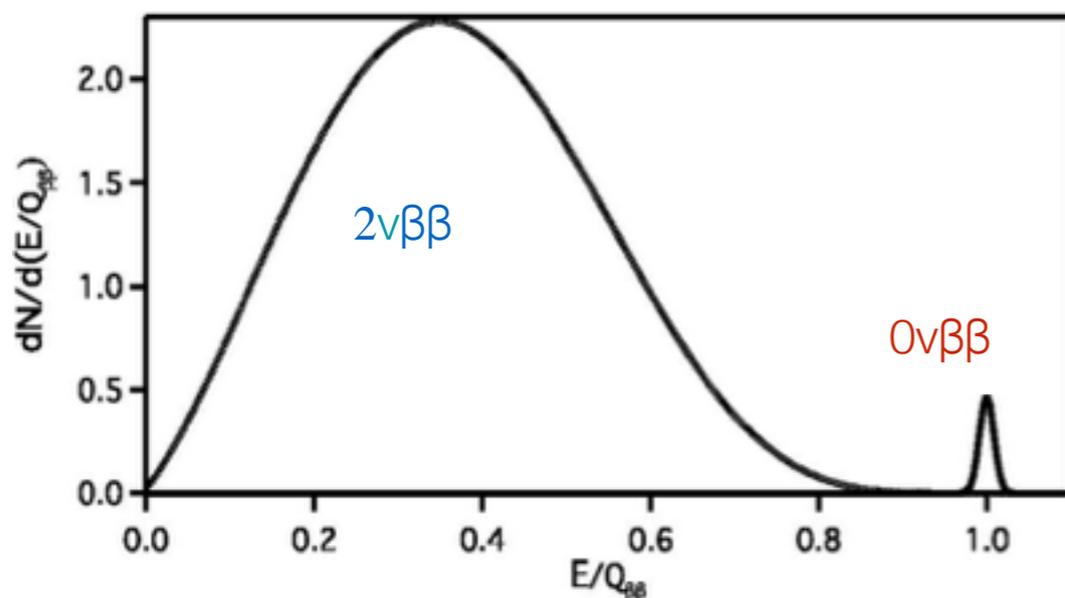
- Large active mass (M) detector
- Long live-time (T)



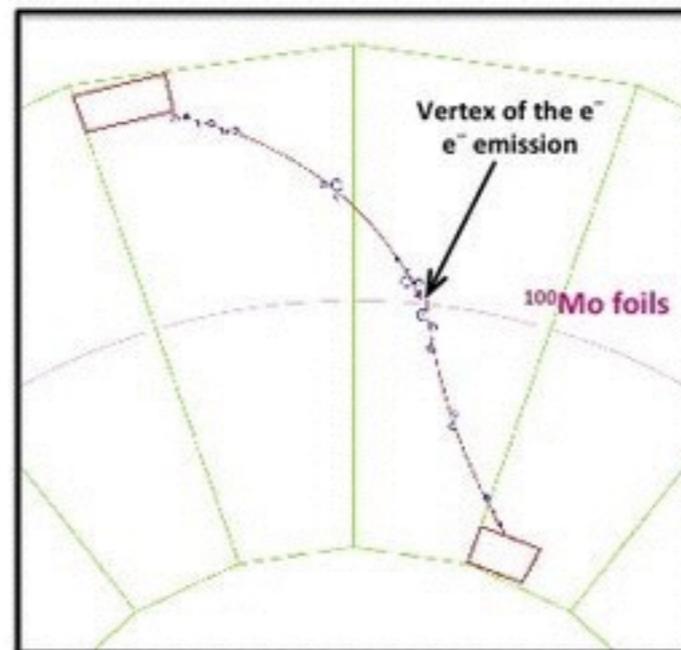
Experimental observables

Experimental observables of double beta decay:

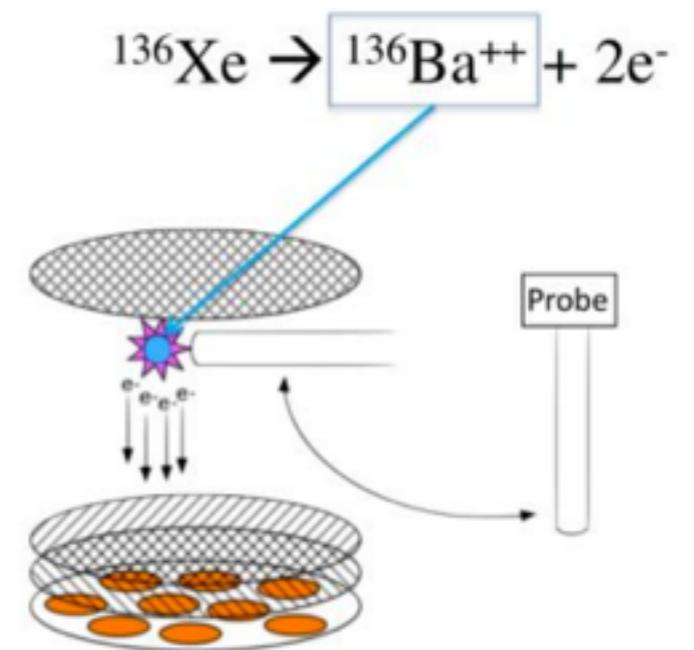
- Cinematic parameters of the two emitted electrons
 - Summed (kinetic) energy of the two electrons
 - Track reconstruction of the single electrons
- Detection of the daughter nucleus, as ion++



Summed energy spectrum of the final state electrons



NEMO-3 tracking calorimeter:
<https://doi.org/10.1080/10619127.2013.793087>

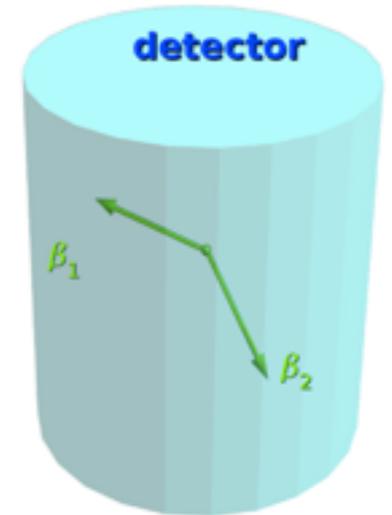


The Enriched Xenon Observatory: EXO-200 and Ba⁺ tagging,
<https://doi.org/10.1016/j.nuclphysbps.2012.09.020>

Experimental searches

The calorimetric approach

- $\beta\beta$ source embedded into the detector: $\varepsilon \sim 1$
- Particle ID: none/partial
- Measurement of the sum energy of the two emitted electrons



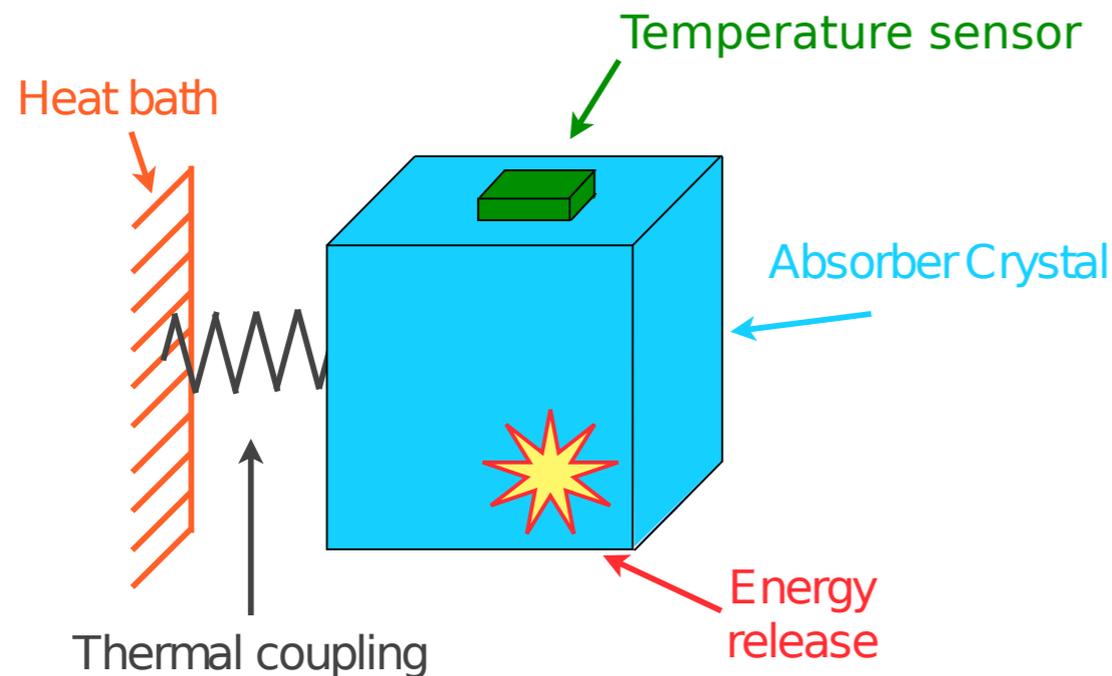
Limiting factor to experimental sensitivity: background

- $2\nu\beta\beta$ irreducible background in the ROI \rightarrow need for: high energy resolution, fast detectors and/or choice of $\beta\beta$ candidates with lower $2\nu\beta\beta$ decay rates
- Cosmic rays and environmental radioactivity \rightarrow underground labs, active/passive veto systems
- Material and detectors activation while above ground (superficial contaminations) \rightarrow high radio purity conditions during construction and storage
- High energy resolution detectors (FWHM/E $\sim 0.15\%$ at $Q_{\beta\beta}$), active mass $\sim 10\text{kg}$ \rightarrow ~ 1 tonne:
 - Ge-diodes (^{76}Ge)
 - **Low temperature detectors (LTD)**: exploitable for all $\beta\beta$ candidates
- Large scale scintillators, active mass $\gg 1$ ton, high radio purity, limitations in energy resolution: ^{136}Xe loaded scintillators

Low temperature detectors

Thermal detectors

Cryogenics calorimeters. An absorber crystal is connected to an 'heat bath' at ~few mK. It is instrumented with a sensor measuring the temperature variation in the crystal induced by a small energy release (~keV/MeV). **The deposited energy is converted into phonons.**



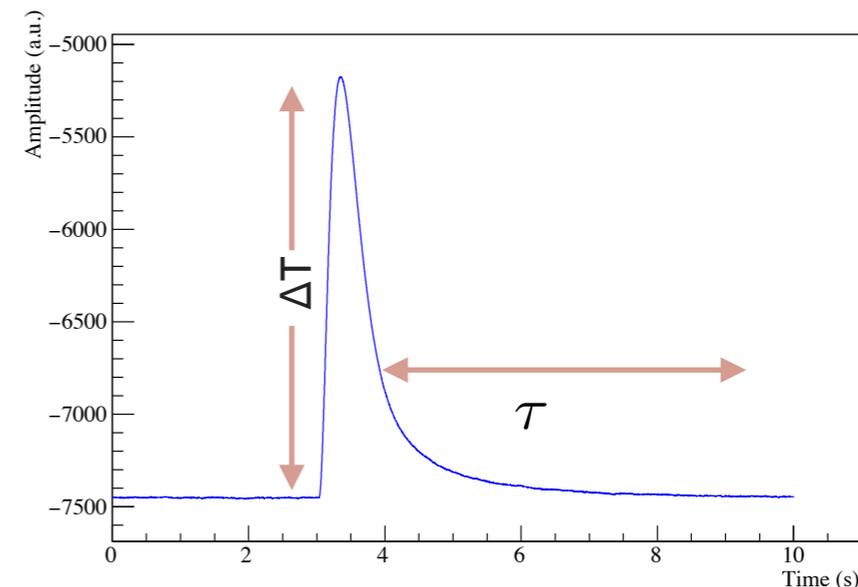
- Absorber at $T \sim 10$ mK
- Energy deposition in the absorber (E_{dep}): particles scattering on electrons and nuclei \rightarrow production of athermal phonons \rightarrow energy degradation \rightarrow thermal phonons/heat $\rightarrow \Delta T$
- Phonon sensor - NTD thermistor: large resistance variation with T (ΔR) \rightarrow generation of an electrical pulse signal with amplitude proportional to the energy of the excess phonons

Simplified thermal model:

One thermal capacity C (crystal)

One thermal link G (btw crystal/heat bath)

$$\Delta T \propto \frac{E_{dep}}{C}$$
$$\tau = \frac{G}{C}$$



Low temperature detectors

Thermal detectors requirements for $\beta\beta$ decay searches

Absorber crystal:

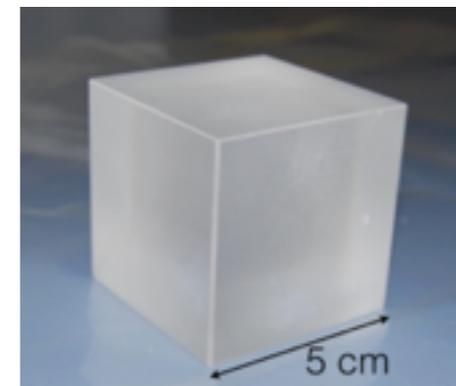
- Contains the $\beta\beta$ candidate isotope
- Low specific heat c of the material at $T \sim 10$ mK
 \rightarrow heat capacity $C = m \cdot c$ (m , crystal mass)
- Weak thermal link G between crystal and heat bath
- Particle ID: scintillating/cherenkov emitting crystals

Phonon sensor

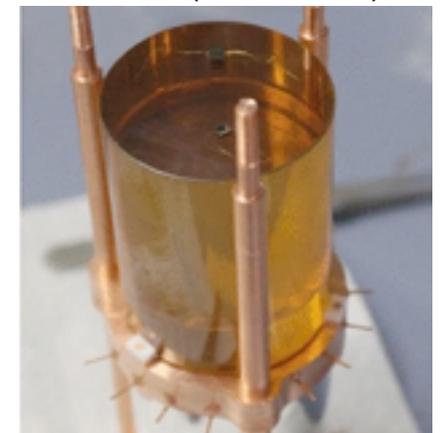
Logarithmic sensitivity - resistance variation: $A = \left| \frac{d \log R}{d \log T} \right|$

- Athermal phonons sensors (TES, MMC): $A \sim 100-1000$, fast ($\sim \mu\text{s}-\text{ms}$), small range of working temperatures, need cold electronics
- **Thermal phonons sensors** (semiconductor NTD thermistors): $A \sim 1-10$, slow ($\sim \text{s}$), bias/read-out circuit at room temperature

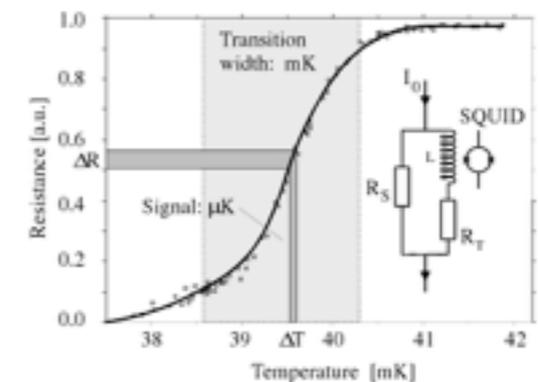
(nat)TeO₂ (CUORE)



ZnSe (CUPID-0)

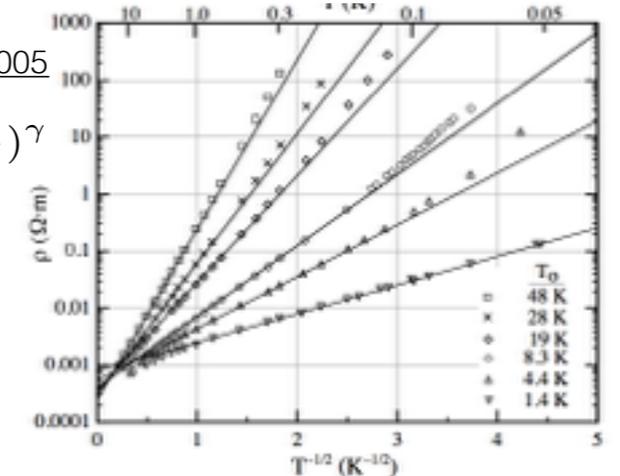
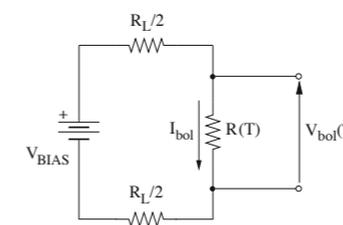


TES: [J. Höhne et al., 1999](#)



Si-NTD: [McCammon, 2005](#)

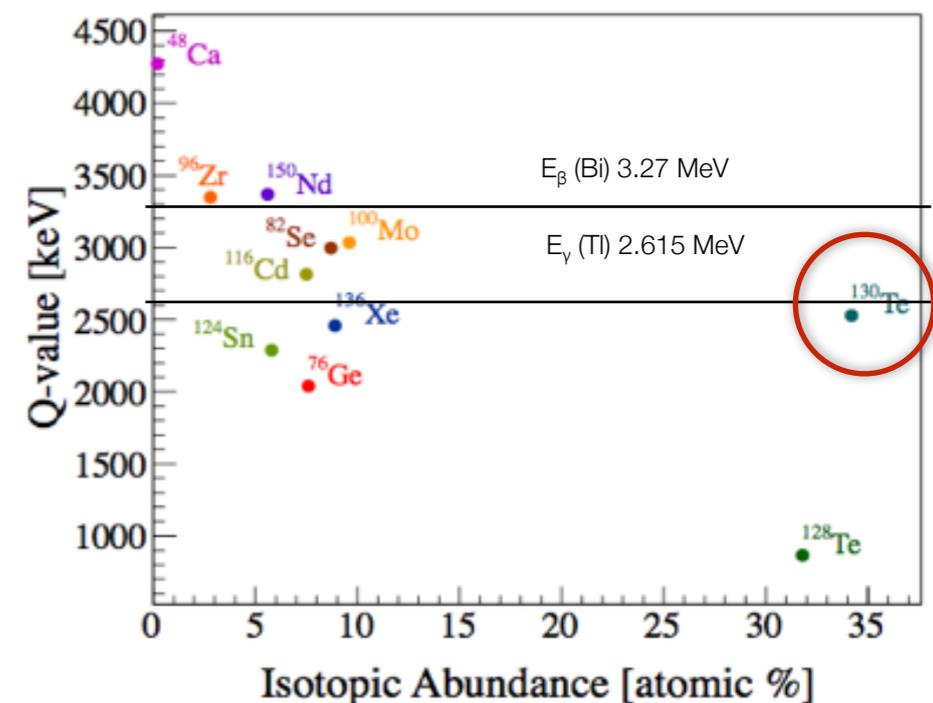
$$\rho(T) = \rho_0 e^{\left(\frac{T_0}{T}\right)^\gamma}$$



Low temperature detectors: TeO_2

Benefits of using $(\text{nat})\text{TeO}_2$ detectors for $\beta\beta$ decay searches:

- ^{130}Te natural isotopic abundance $\eta(^{130}\text{Te}) = 34.167\%$, no need for further enrichment after the growth of natural crystals
- $Q_{\beta\beta}(^{130}\text{Te}) = 2527.518 \text{ keV}$, above most of the natural radioactivity
- ^{130}Te within the detector absorber of TeO_2 ($\varepsilon \sim 90\%$)
- Reproducible growth of large number of high quality and high purity crystals; **large active mass detector** (crystals $\sim 1\text{kg}$, ~ 1000 crystals)
- TeO_2 operated as **low temperature detectors** ($\sim 10 \text{ mK}$): **very good energy resolution** Δ ($\sim 0.1\text{-}0.2\%$ FWHM/E at $Q_{\beta\beta}$), allows a better reconstruction of the background spectrum and a reduction of $2\nu\beta\beta$ decay irreducible background around $Q_{\beta\beta}$



The CUORE experiment

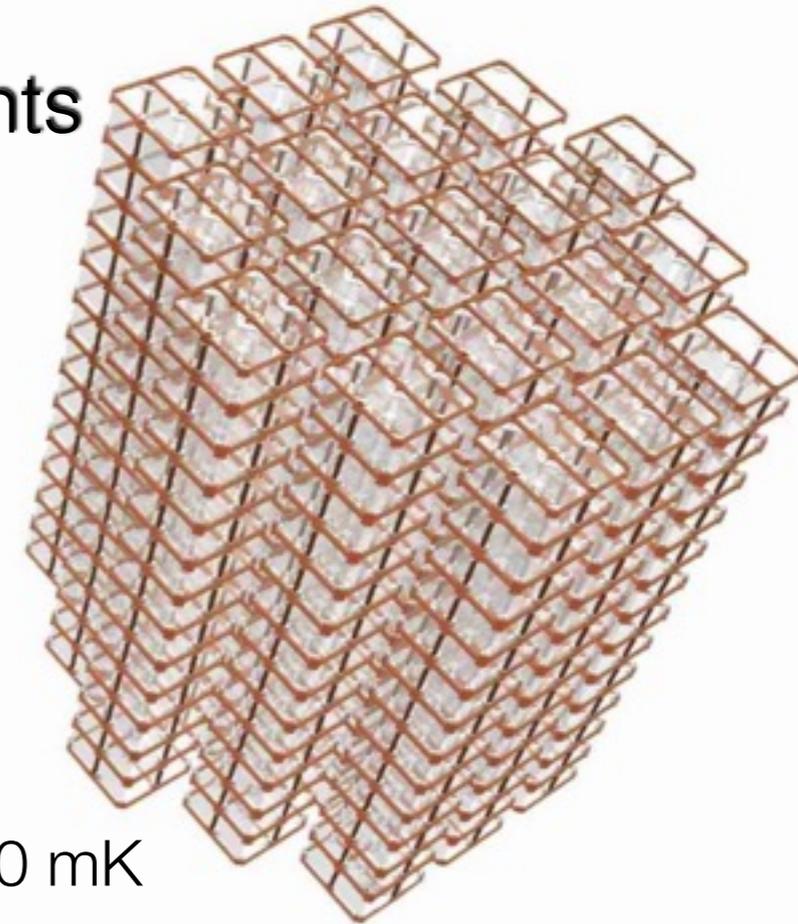
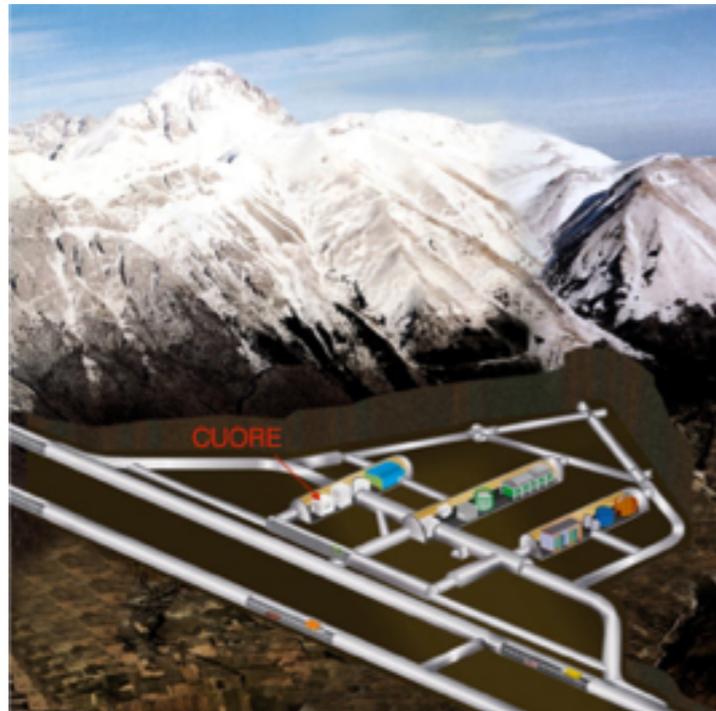


CUORE:

Cryogenic Underground Observatory for Rare Events

Experiment for rare events physics,
in particular search for $0\nu\beta\beta$ decay of ^{130}Te .

Located at Laboratori Nazionali del Gran Sasso (LNGS)



Utilizing low temperature detectors.

988 $(\text{nat})\text{TeO}_2$ crystals operated at ~ 10 mK

742 kg TeO_2 , 206 kg ^{130}Te

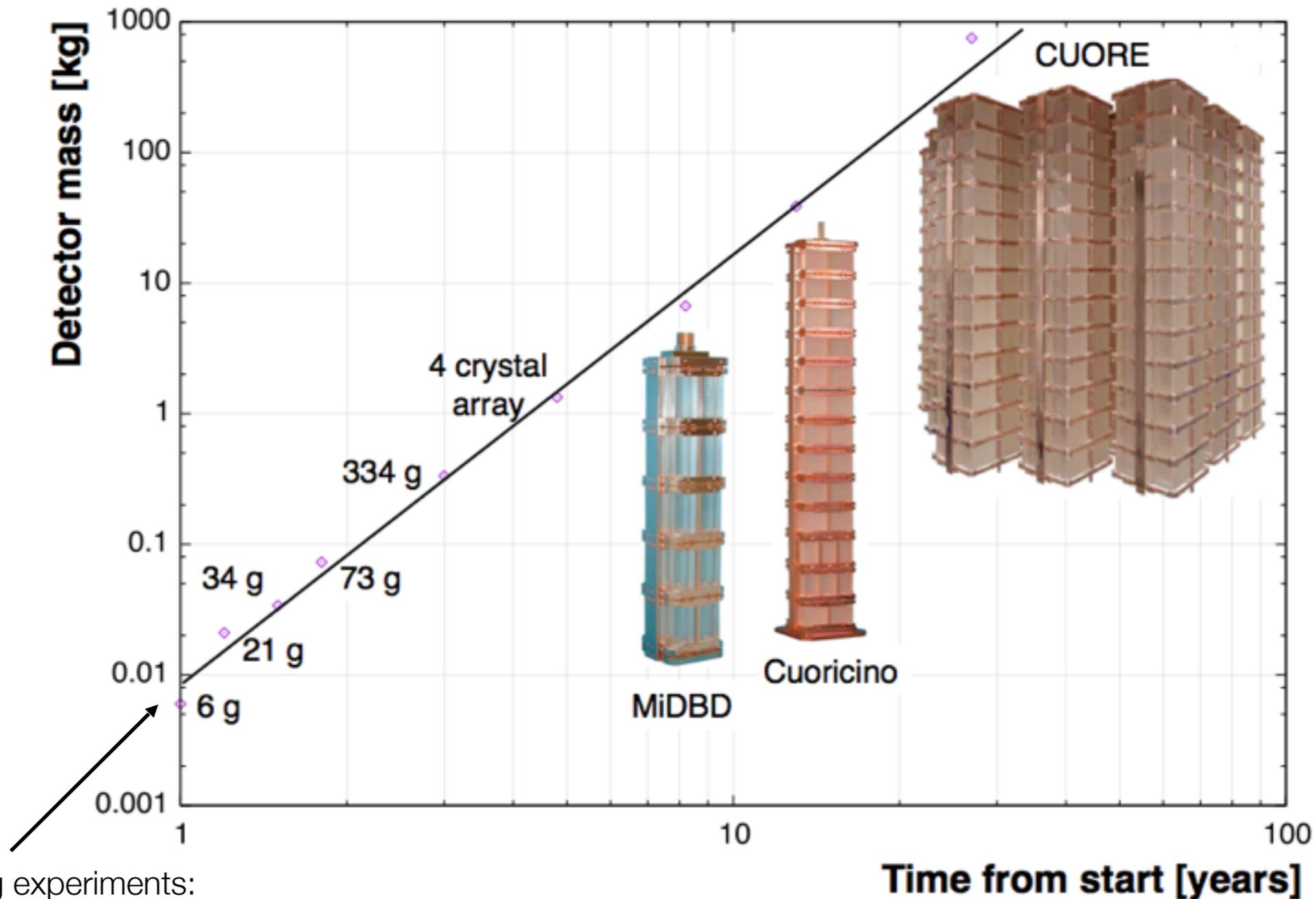
- large mass and high granularity -

Cryogenic solid state calorimeter at the ~ 1 tonne scale

The CUORE experiment

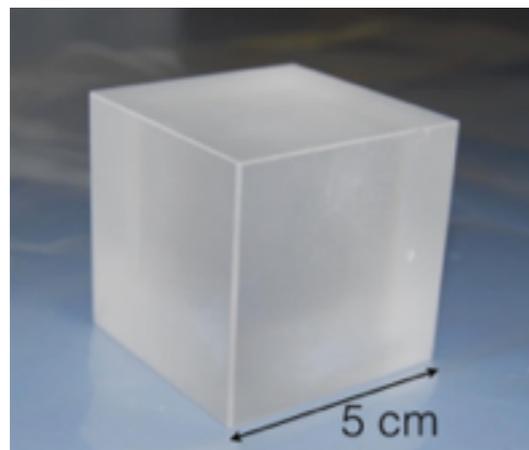
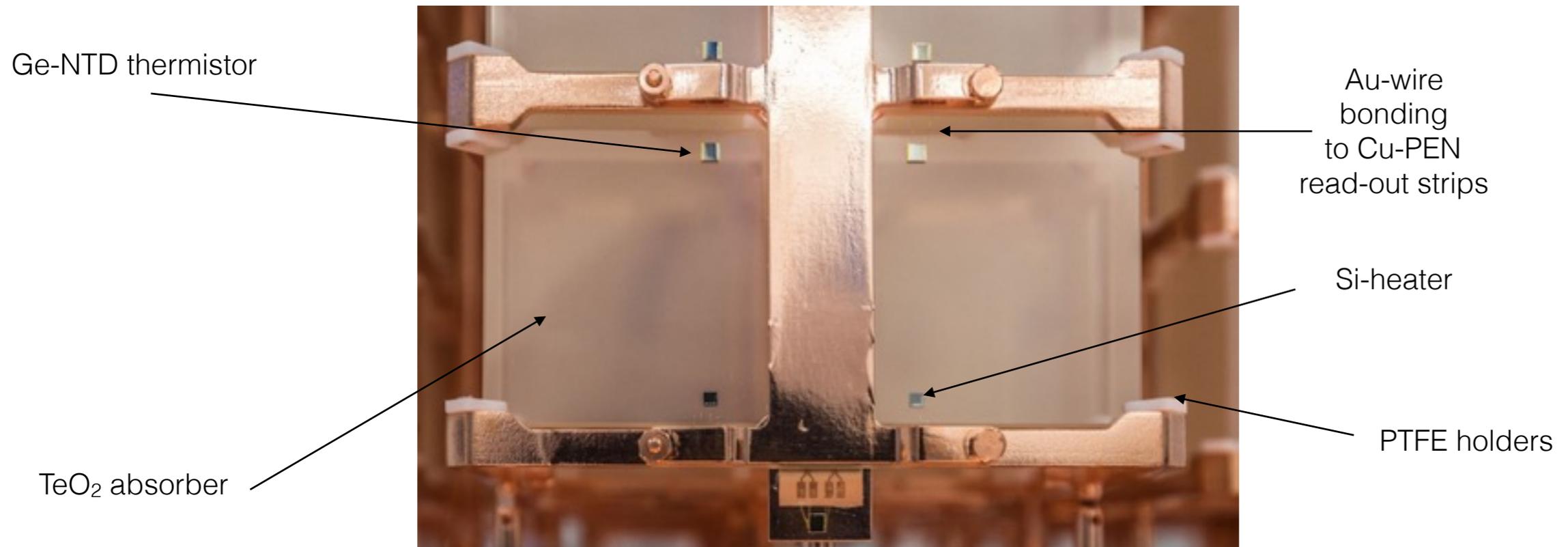


From few g to 1 tonne TeO_2 cryogenic calorimeters for double beta decay search

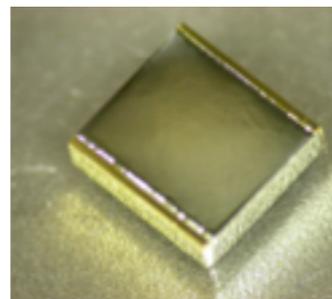


Pioneering experiments:
E.Fiorini group in Milano in the 1980s

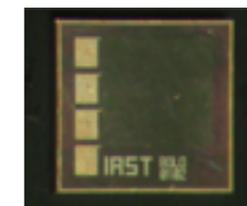
The CUORE detectors



$^{nat}\text{TeO}_2$ crystal
 Absorber = $0\nu\beta\beta$ source
 $5.0 \times 5.0 \times 5.0 \text{ cm}^3$, 750 g mass
 $\Delta T_{\text{crystal}} \sim 100 \mu\text{K/MeV}$ (@10 mK)



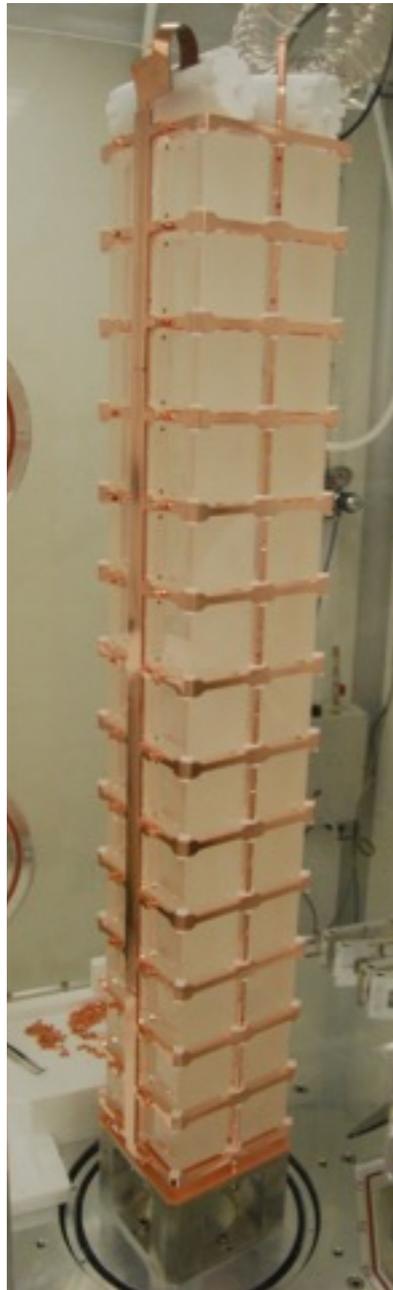
NTD-Ge thermistor
 $3.0 \times 2.9 \times 0.9 \text{ mm}^3$
 Working impedance of the thermistors:
 $R_{\text{wp}} \sim 100 \text{ M}\Omega - 1 \text{ G}\Omega$
 $\rightarrow \Delta V_{\text{NTD}} \sim 400 \mu\text{V/MeV}$ (@10 mK)



Si heater
 $2.3 \times 2.4 \times 0.5 \text{ mm}^3$
 Joule heater designed to periodically provide a fixed amount of energy in the crystal for gain stabilization

 Alduino C. et al. (CUORE collaboration), J. Inst. 11(07), P07009, (2016)
<https://doi.org/10.1088/1748-0221/11/07/p07009>

The CUORE detectors



CUORE single-module: a tower
52 crystals,
13 floors of 4 crystals each

CUORE detector
Array of closely packed 988
 TeO_2 crystals arranged
in 19 towers



The CUORE challenge

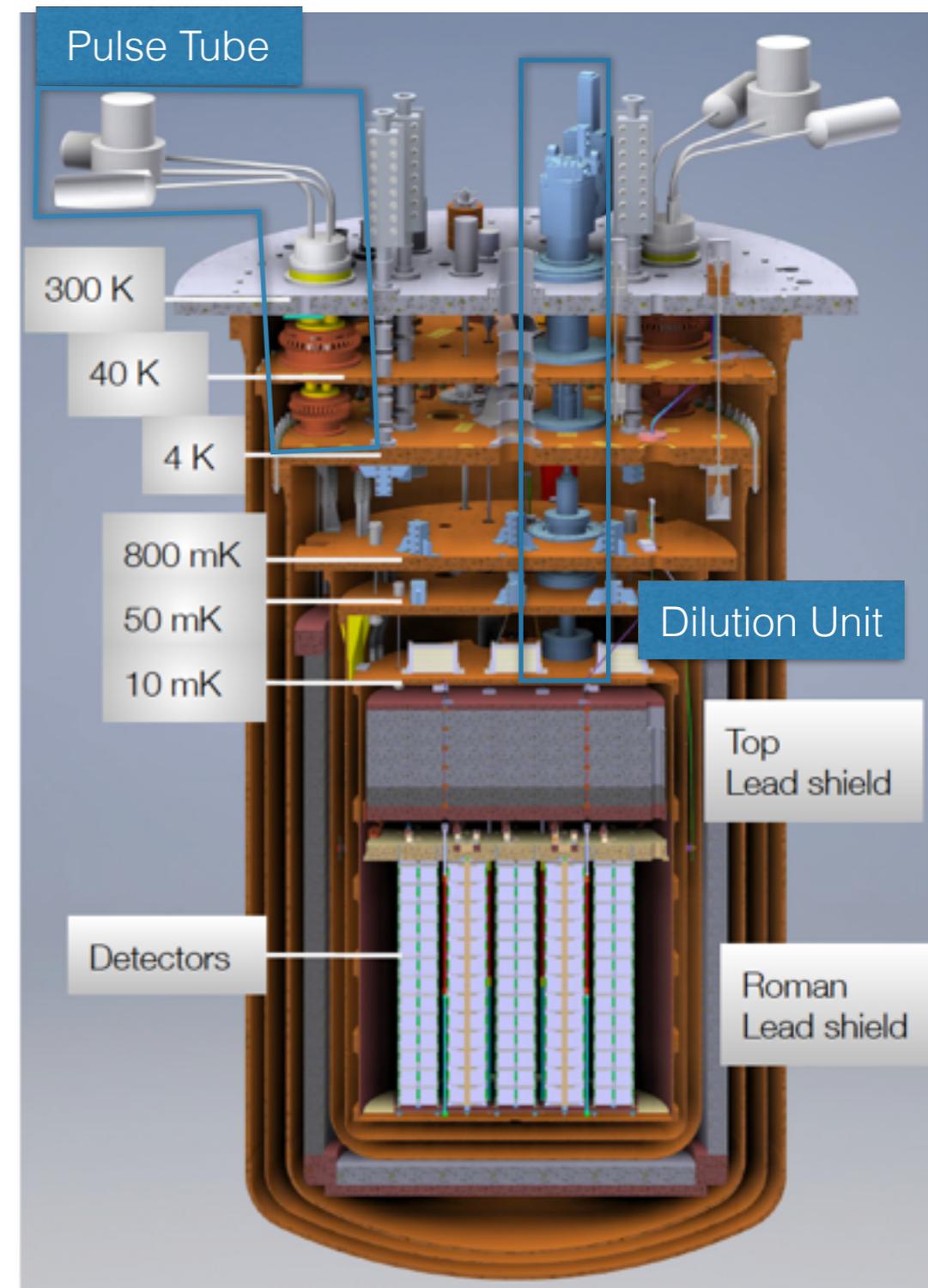
* Low temperature and low vibrations

TeO₂ detectors to be operated as bolometers at temperature ~10 mK: need for cryogenic infrastructure

- Multistage cryogen-free cryostat:
Cooling systems: Pulse Tubes (PTs) and Dilution Unit (DU)
 - Mass to be cooled < 4K: ~ 15 tons (IVC volume and Cu vessels, Roman Pb shield)
 - Mass to be cooled < 50 mK: ~ 3 tons (Top Pb shield, Cu supports and TeO₂ detectors)
- Mechanical vibration isolation
Reduce energy dissipation by vibrations

Target energy resolution: 5 keV FWHM

in the Region Of Interest (ROI) around $Q_{\beta\beta}$



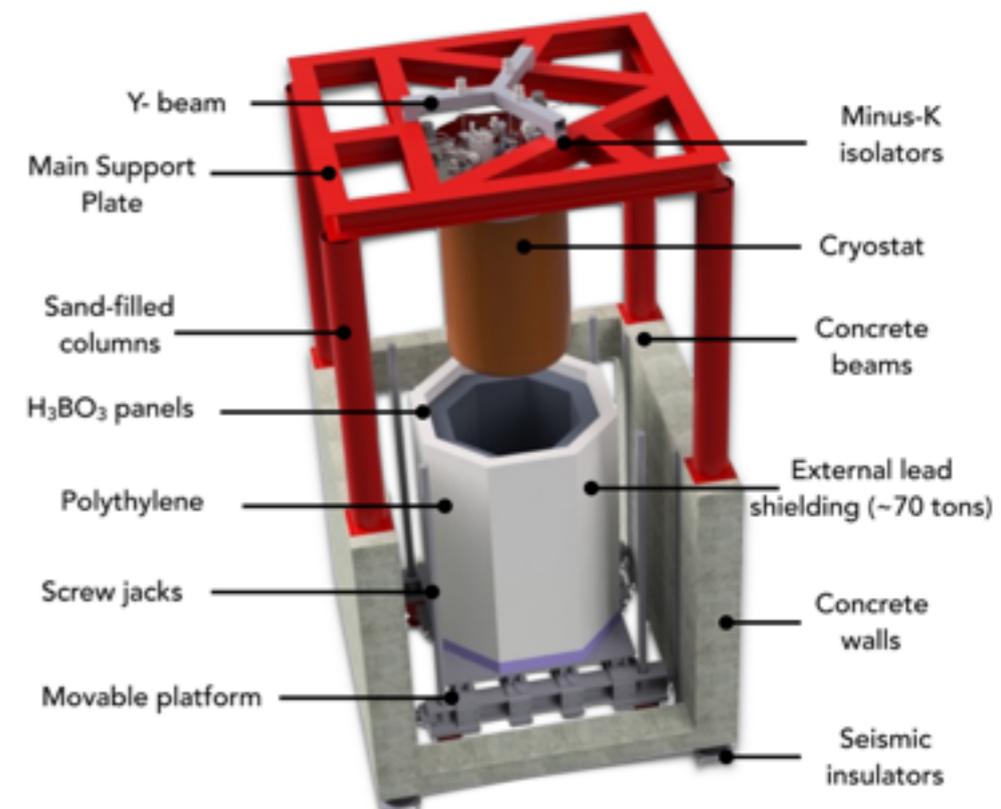
The CUORE challenge

❖ Low background

- Deep underground location (LNGS)
 - Overburden: 1400 m calcareous rock (3600 m.w.e)
 - Cosmic ray rate reduction: 10^{-6} relative to the surface
 - Strict radio-purity controls on materials and assembly
 - Passive shields (Pb) from external and cryostat radioactivity
 - Detector: high granularity and self-shielding
- Background goal: 10^{-2} c/(keV·kg·yr)**
in the Region Of Interest (ROI) around $Q_{\beta\beta}$

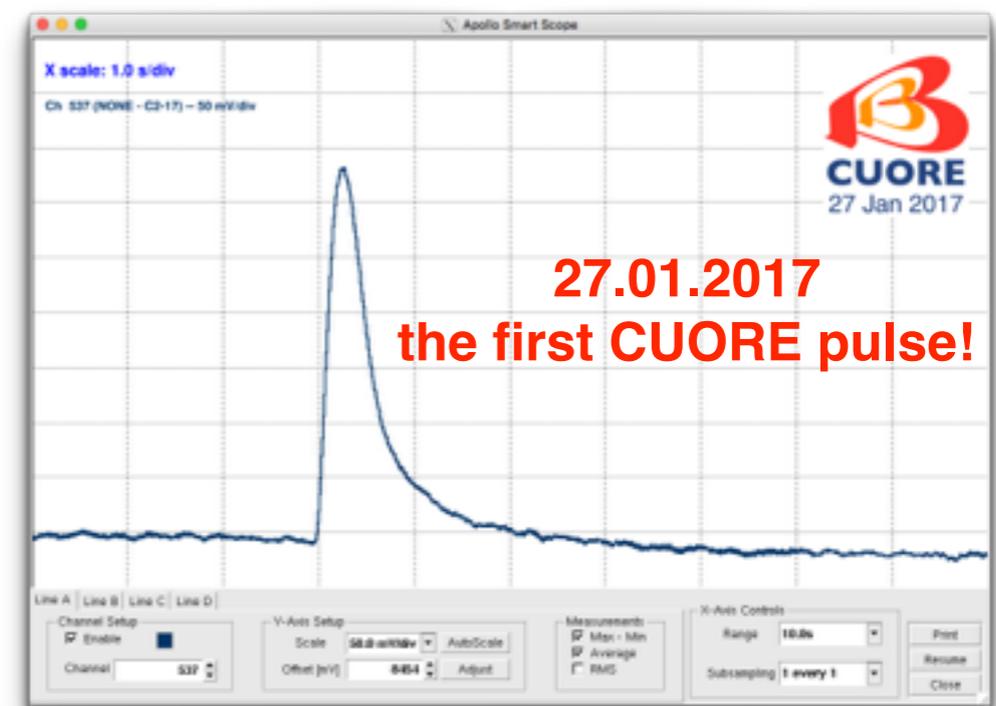
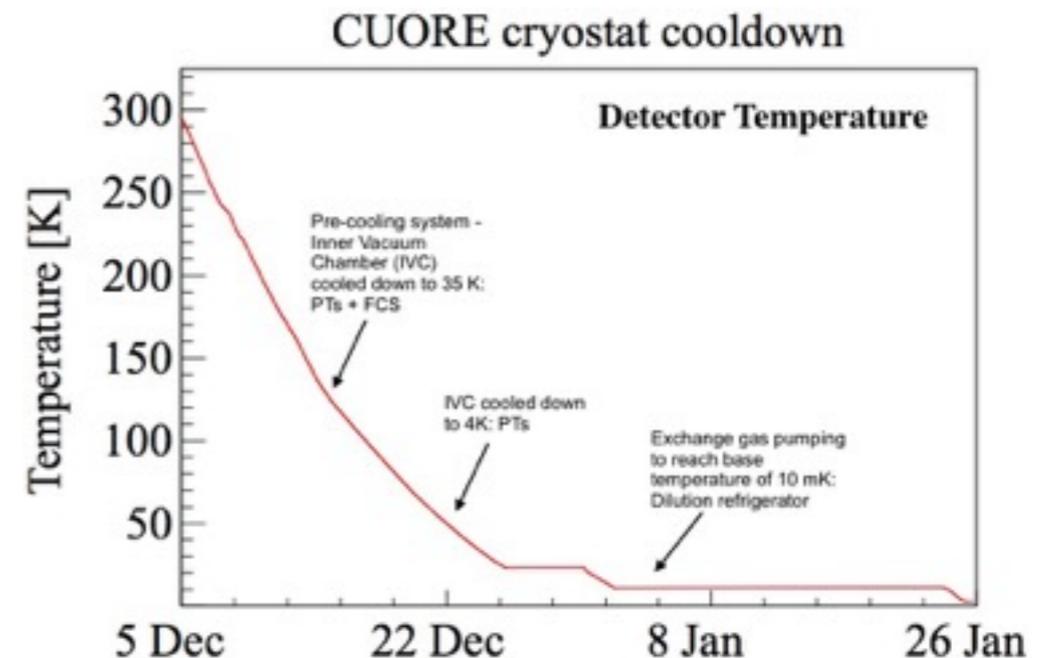
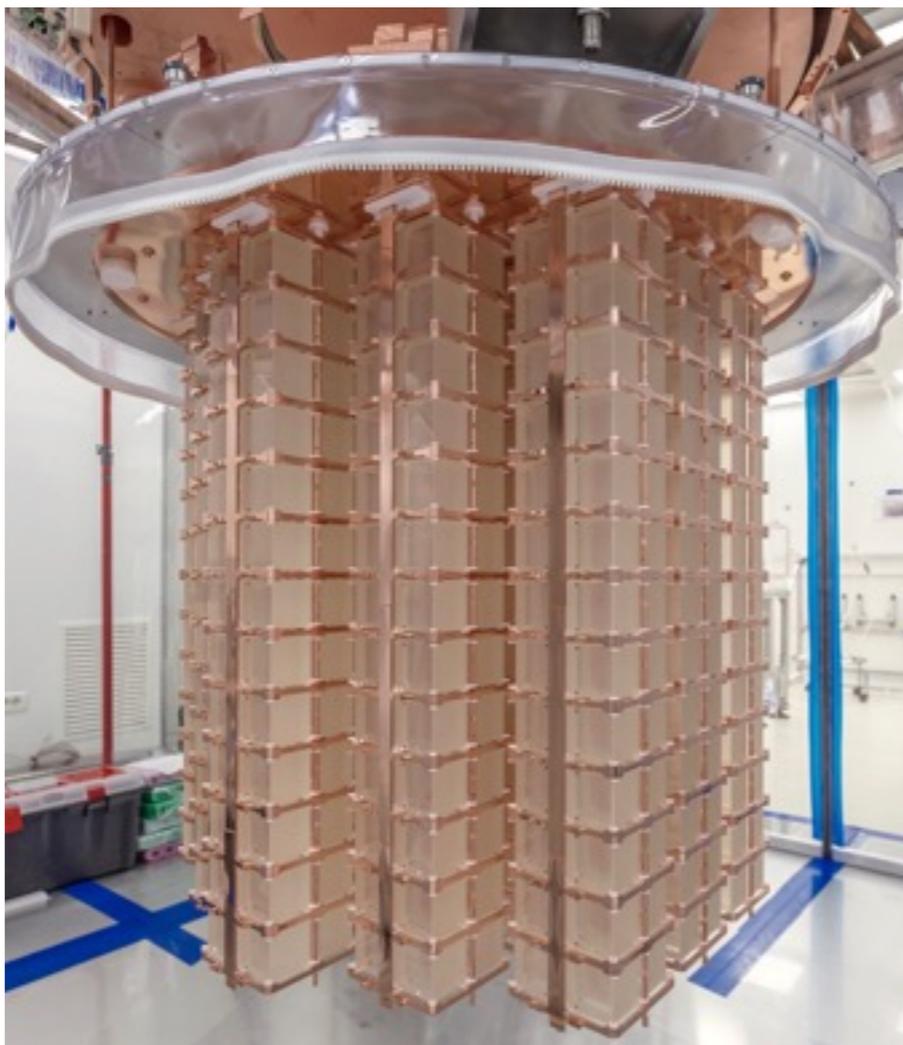


Roman lead shield
(^{210}Pb depleted)
@ 4K



CUORE initial operations

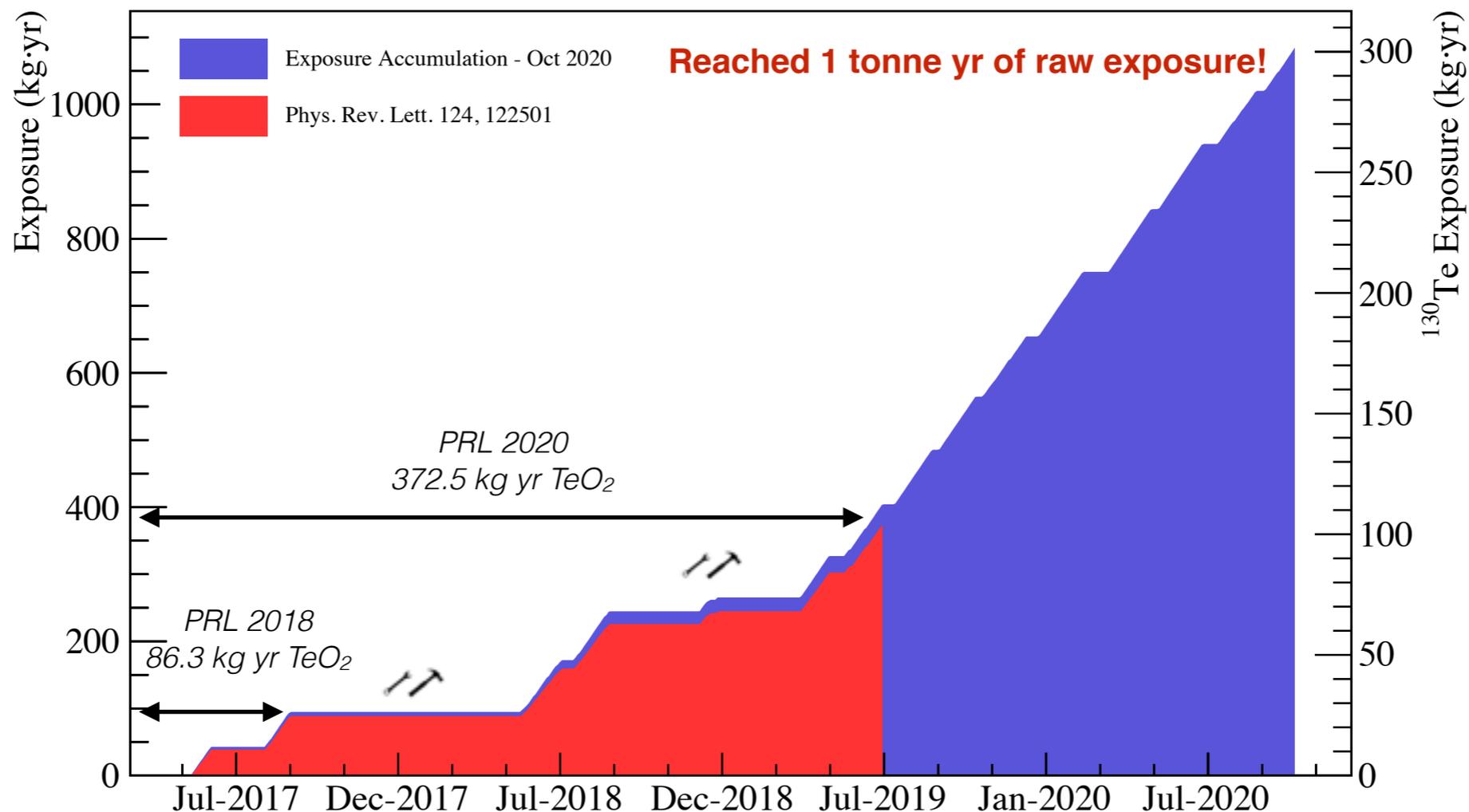
- Cryogenic system commissioning
- Detector assembly and installation
- First Detector cool-down: Started at the beginning of Dec. 2016



CUORE data-taking



- Data taking started in Spring 2017
- After initial data taking phase, significant effort devoted to understanding the system and optimizing data taking conditions
- Since March 2019 data taking is continuing smoothly with > 90% uptime



 Alduino C. et al. (CUORE collaboration), Phys. Rev. Lett. 120, 132501, (2018), <https://doi.org/10.1103/PhysRevLett.120.132501>

 Alduino C. et al. (CUORE collaboration), Phys. Rev. Lett. 124, 122501, (2020), <https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.124.122501>

CUORE optimization

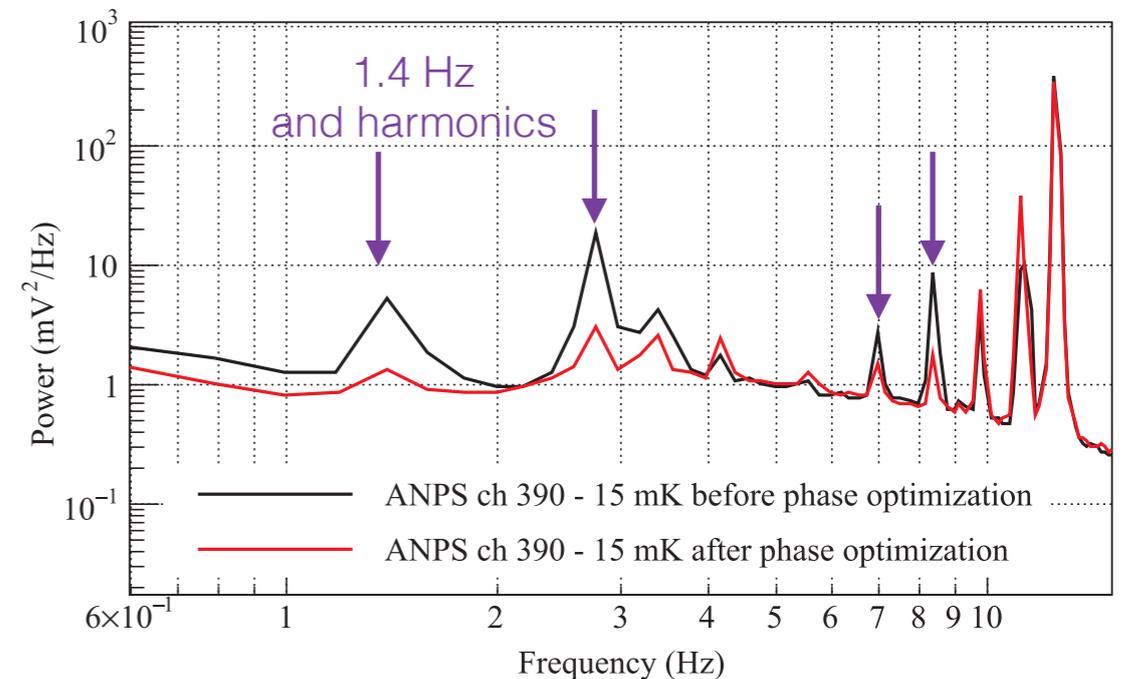
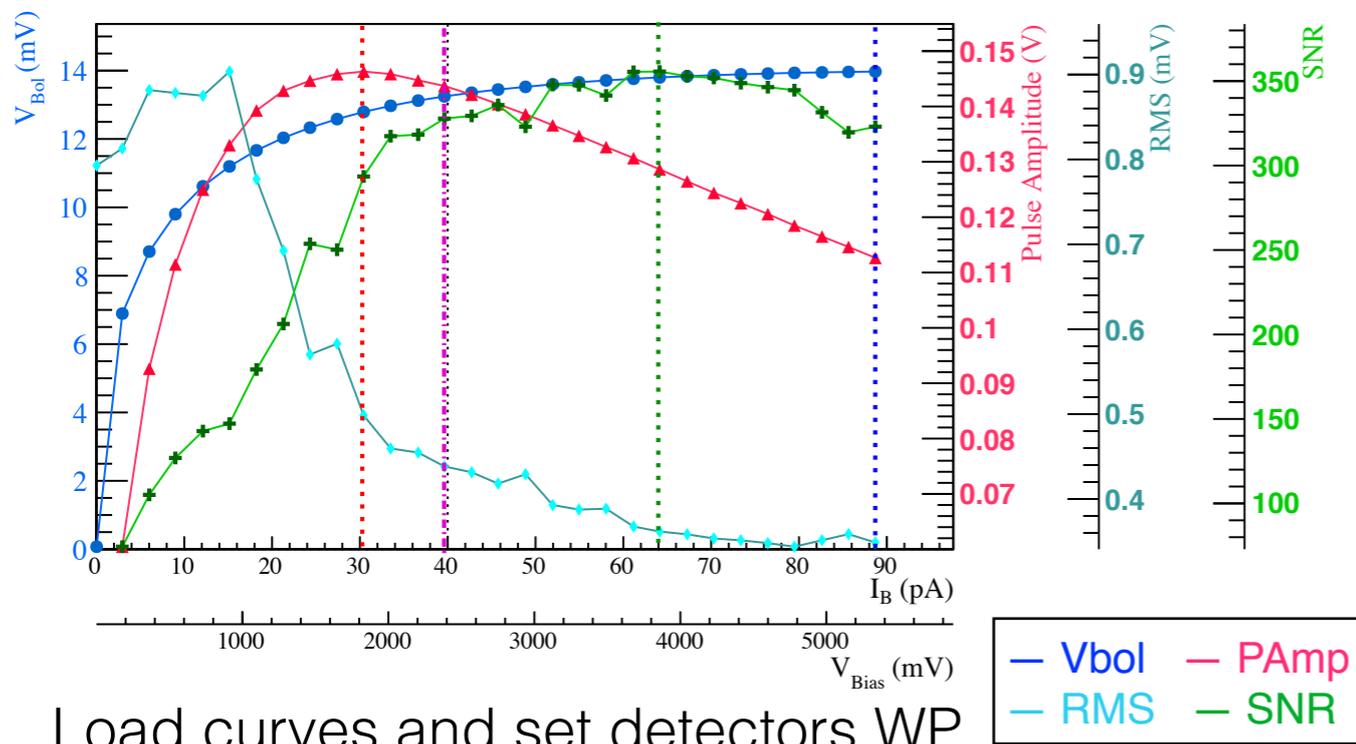
- ❖ First time such a large number of bolometric detectors (~1000) simultaneously operated in a completely new and unique cryogenic system
- ❖ Detector and overall system different compared to previous smaller scale bolometric experiments

Detector optimization campaigns

I.Nutini for the CUORE collaboration, J.Low Temp.Phys. 199 (2020) 1-2, 519-528
<https://doi.org/10.1007/s10909-020-02402-9>

Goal: Improve the energy resolution and reach stable data-taking conditions

- Characterization and tuning of detector operating parameters
- Noise reduction



Load curves and set detectors WP

Pulse Tubes active noise cancellation

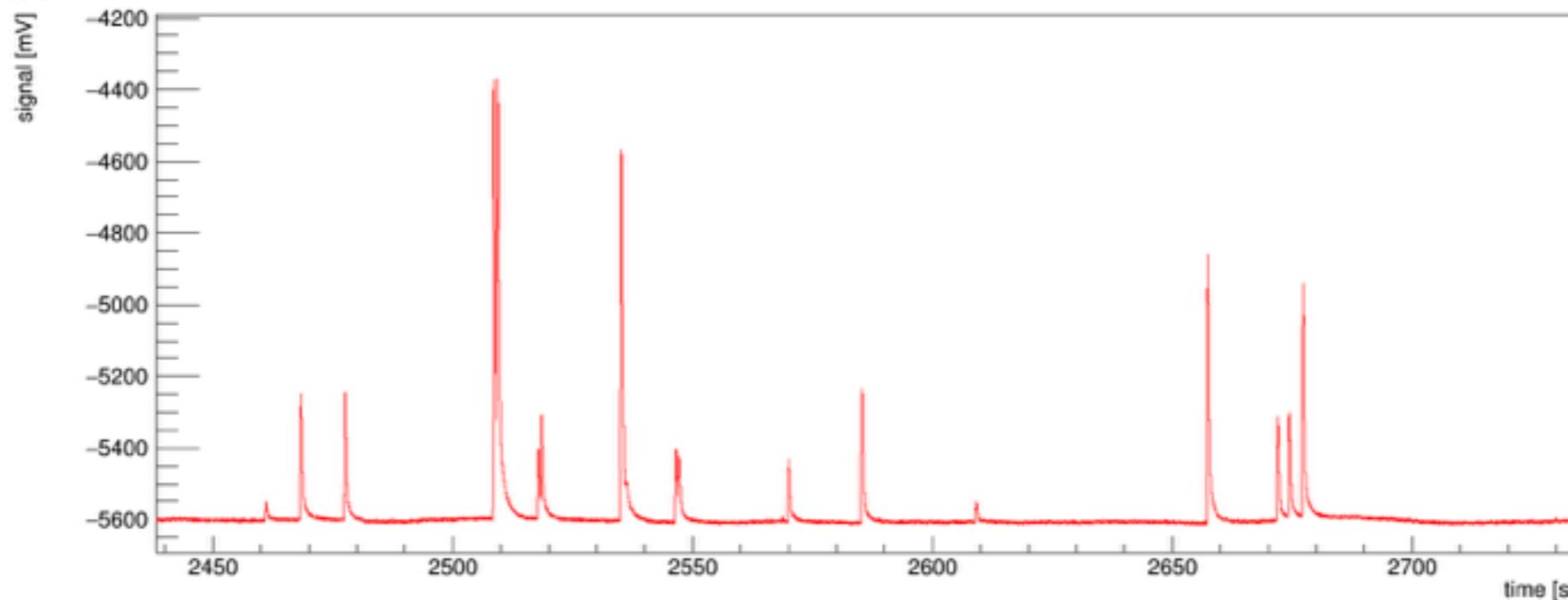
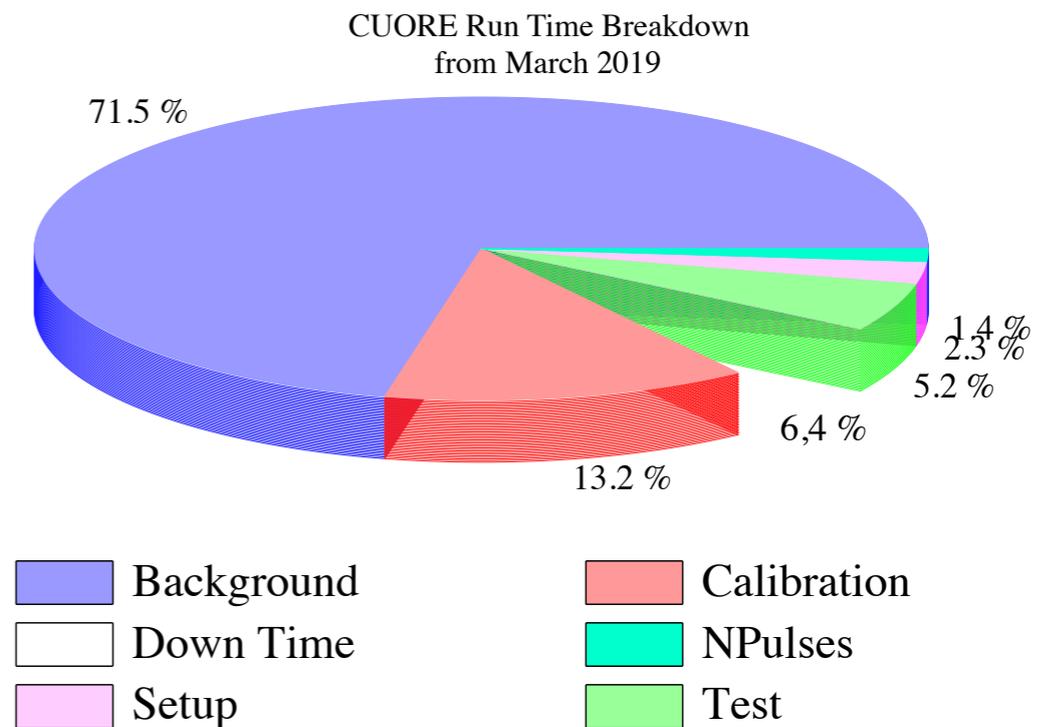
Alfonso K. et al., arXiv:2007.06966 (submitted to JINST)
<https://arxiv.org/abs/2007.06966>

D'Addabbo A. et al., Cryogenics 93, 55-56, (2018)
<https://doi.org/10.1016/j.cryogenics.2018.05.001>

CUORE physics runs



- CUORE “data set”: ~1 month of background data taking with a few days of calibration at the start and end
- Operational performance: 984/988 operational channels
- The voltage output from the detectors is sampled at 1kHz and saved into a data-stream
- The analysis procedure aims to **trigger** the signal pulses, measure their **amplitude (energy)** and reject spurious events



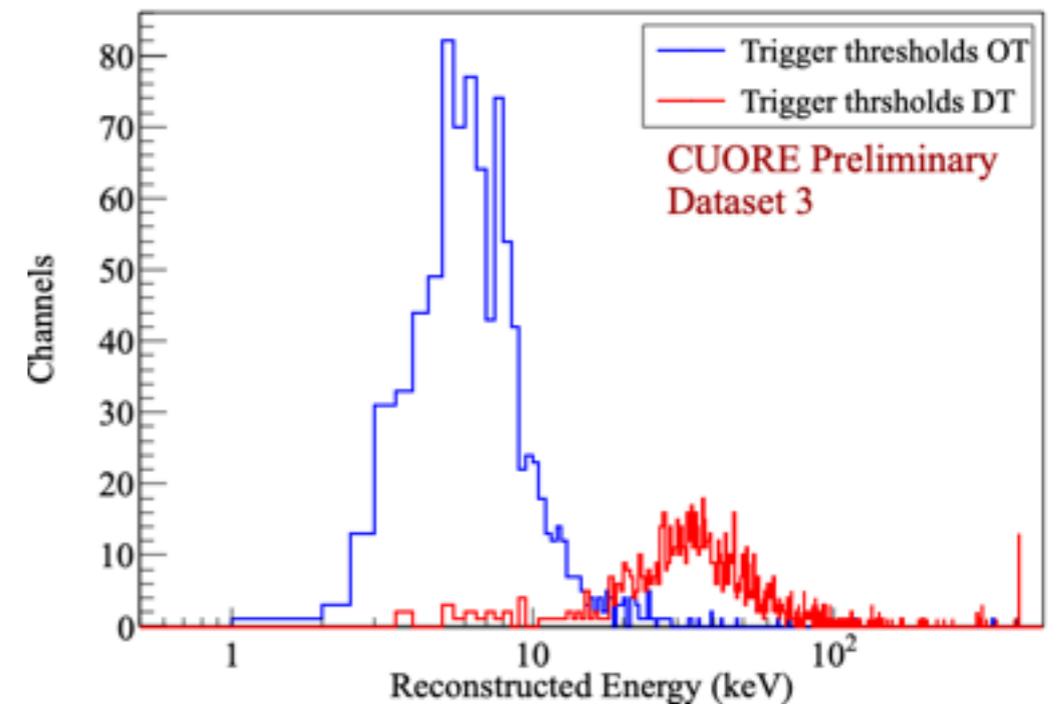
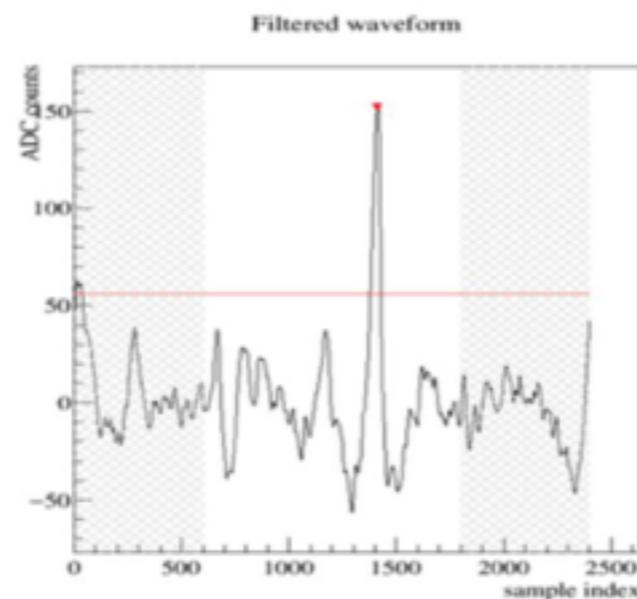
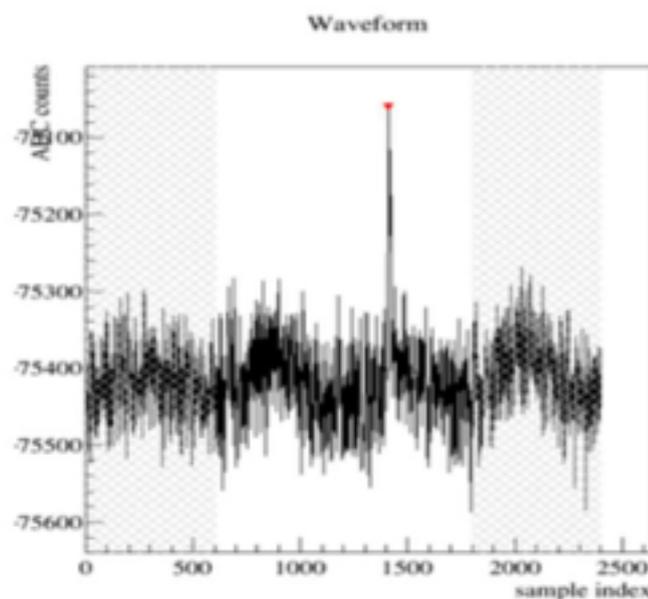
CUORE data-processing



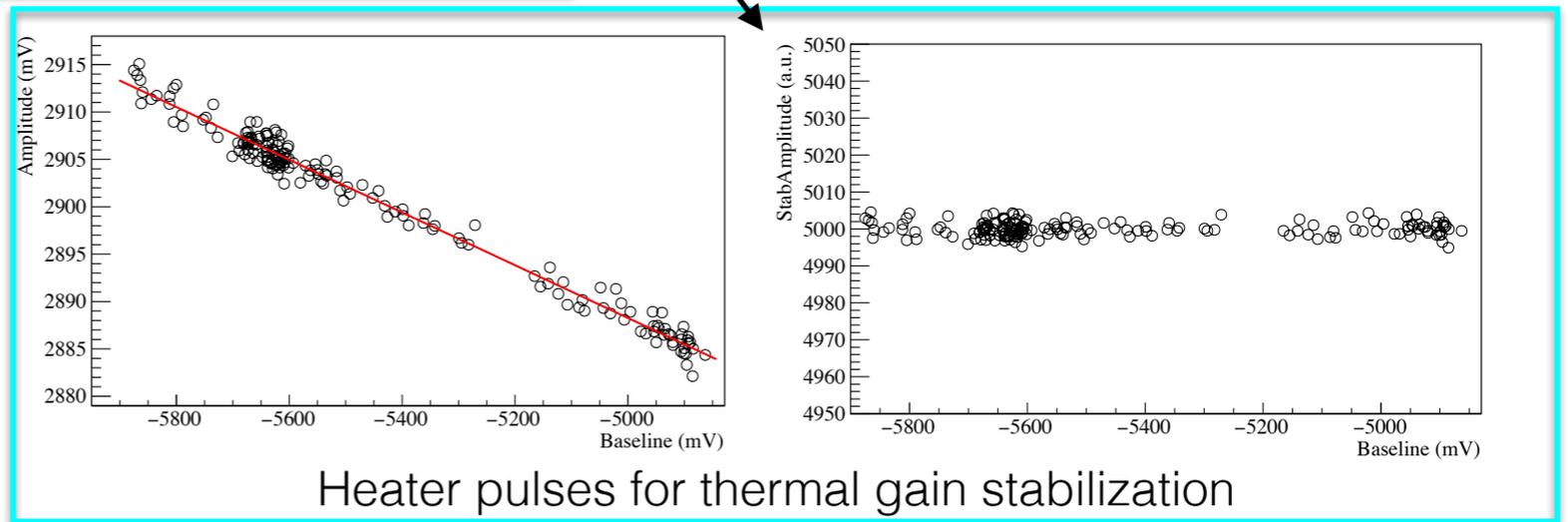
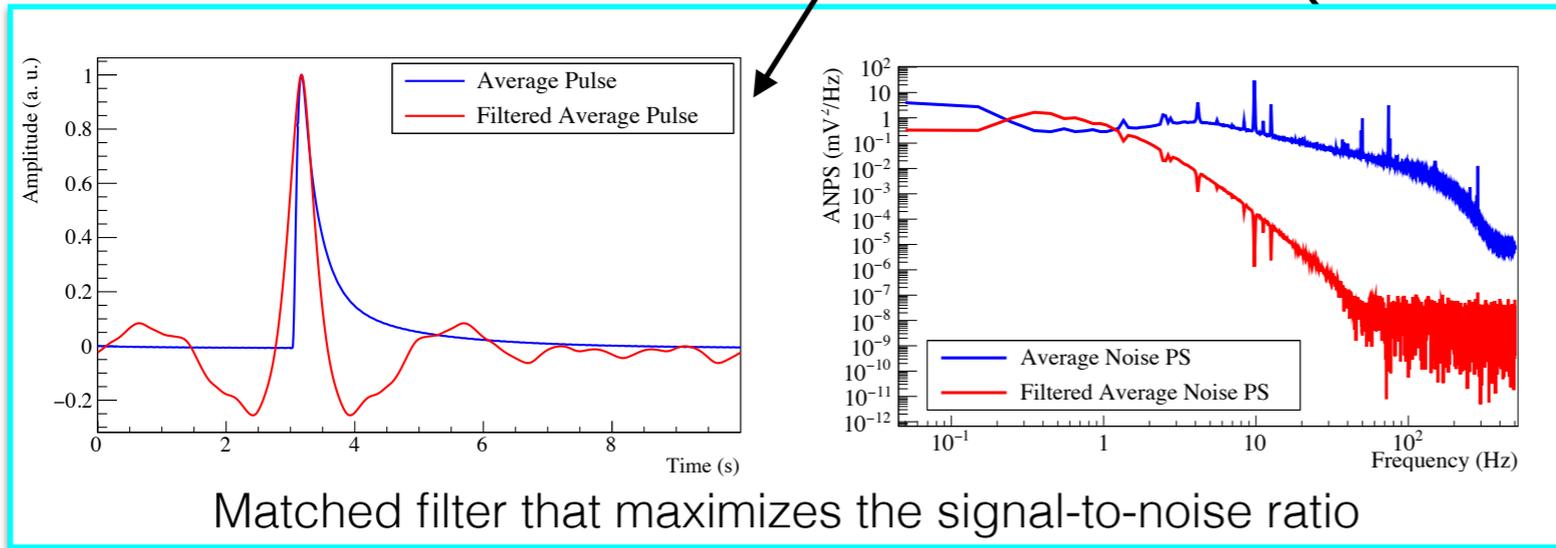
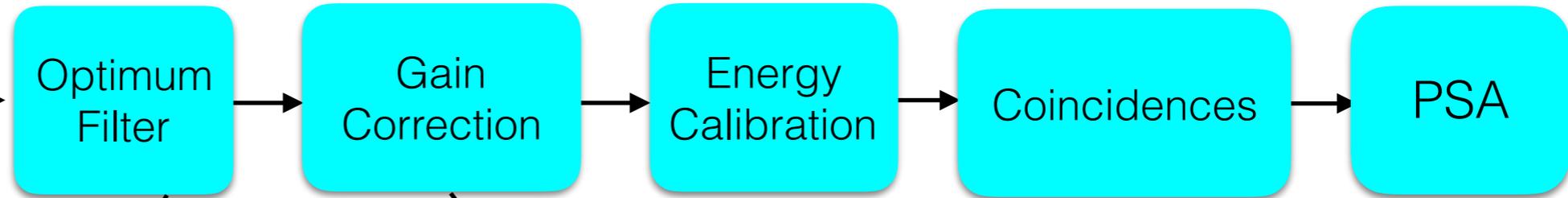
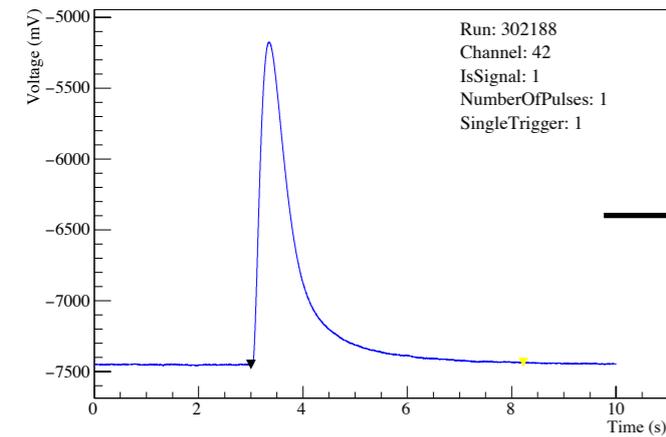
Triggering pulses

- Online Derivative Trigger (DT): threshold on the derivative of the data-stream
- Offline Optimal Trigger (OT): identification of pulses in the data-stream by applying a template-filter (expected pulse shape wrt to expected noise)

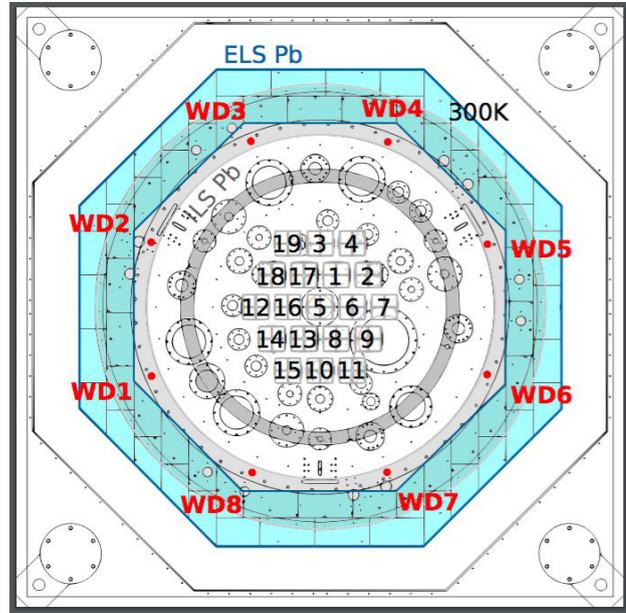
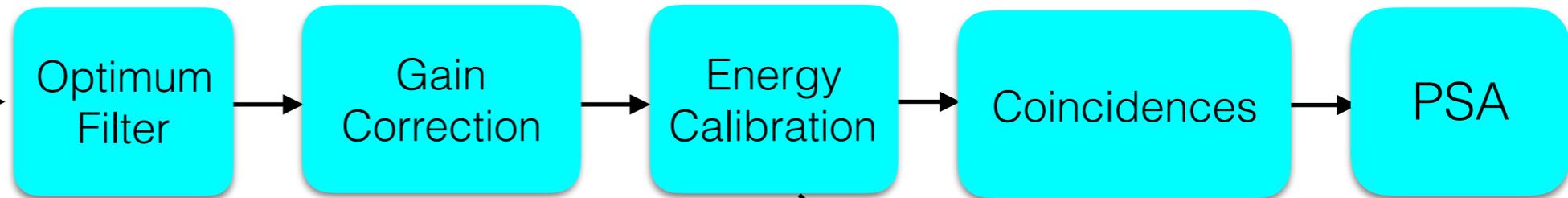
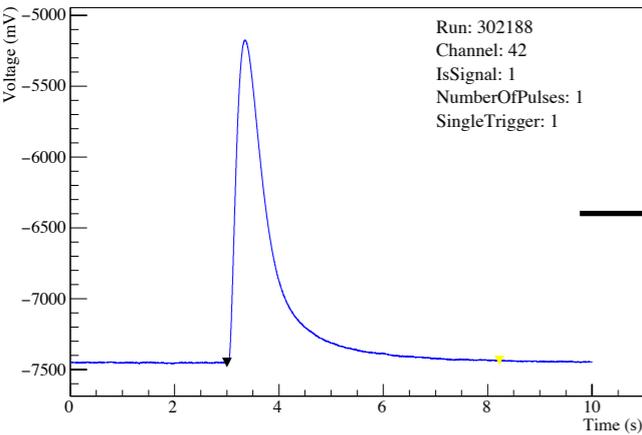
Thresholds: DT ~ 50 keV, OT < 10 keV



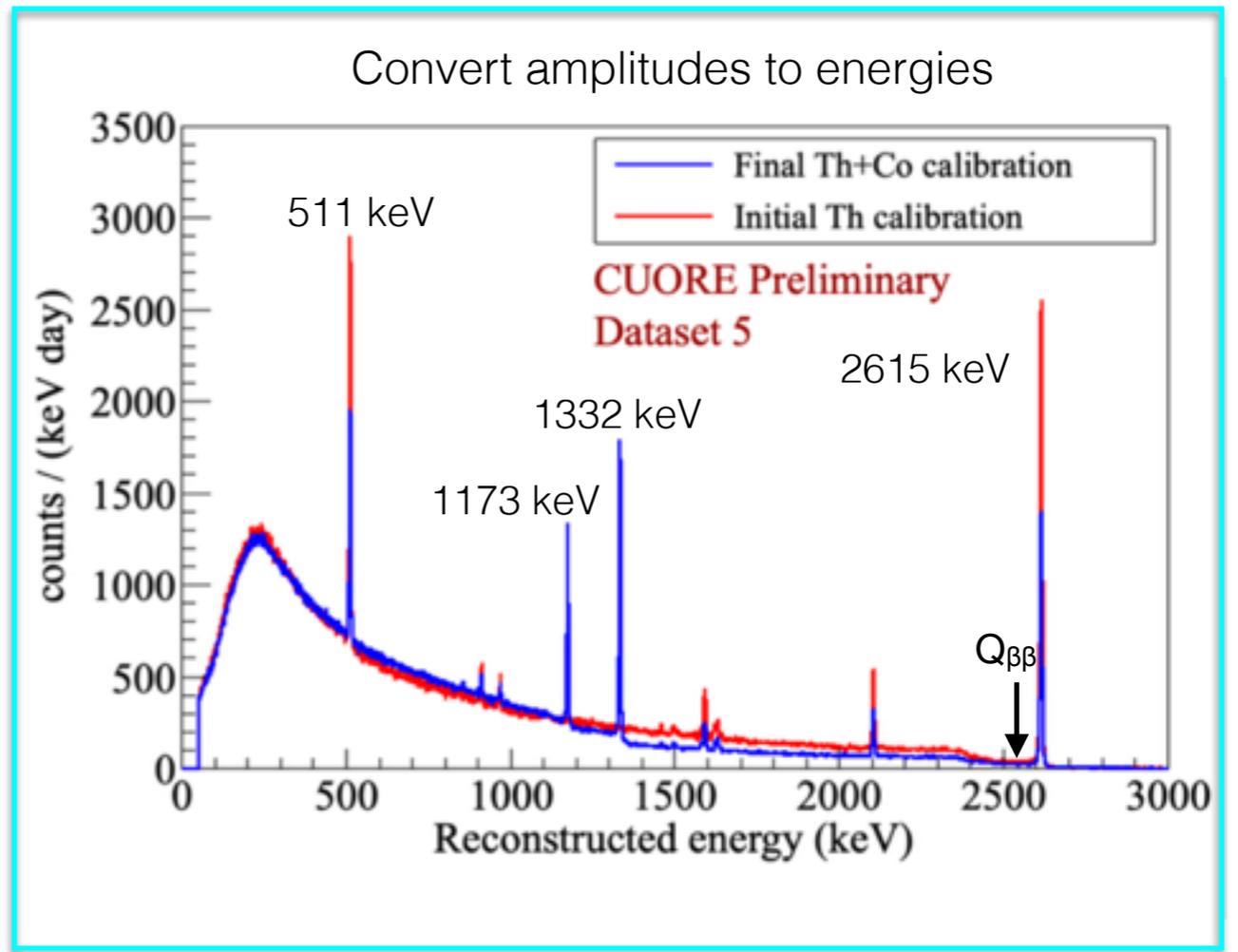
CUORE data-processing



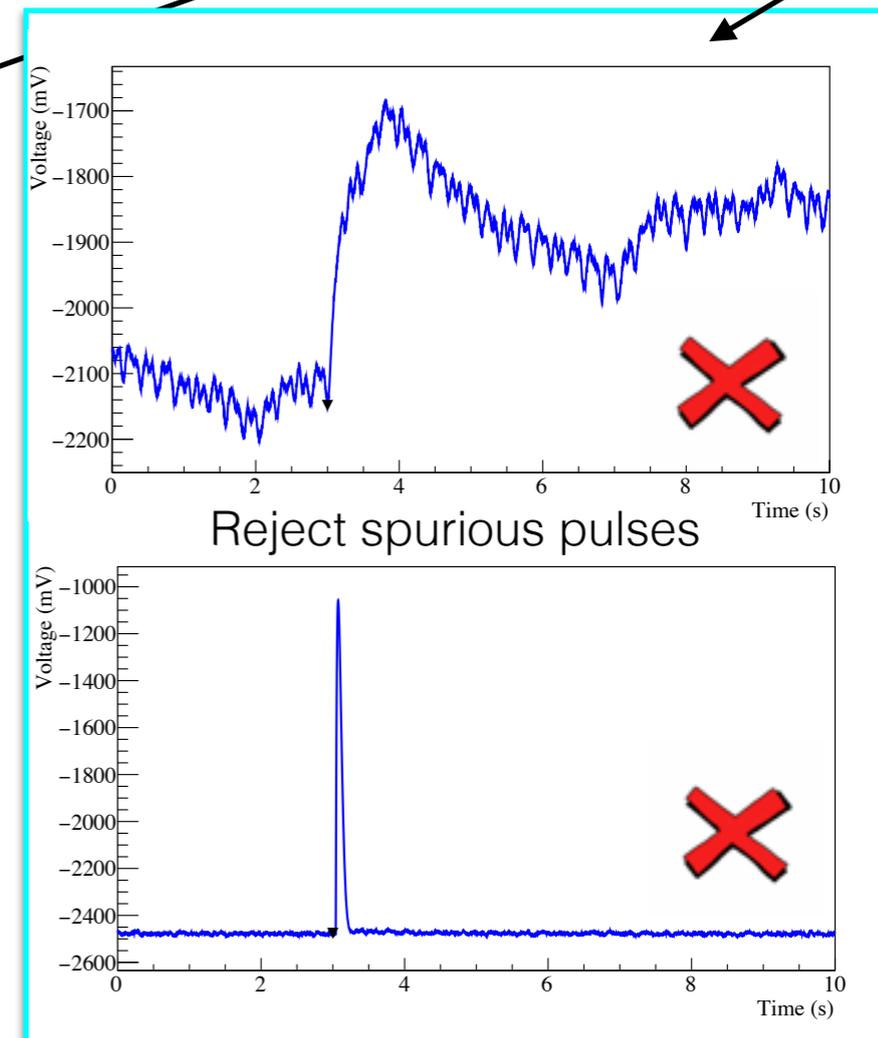
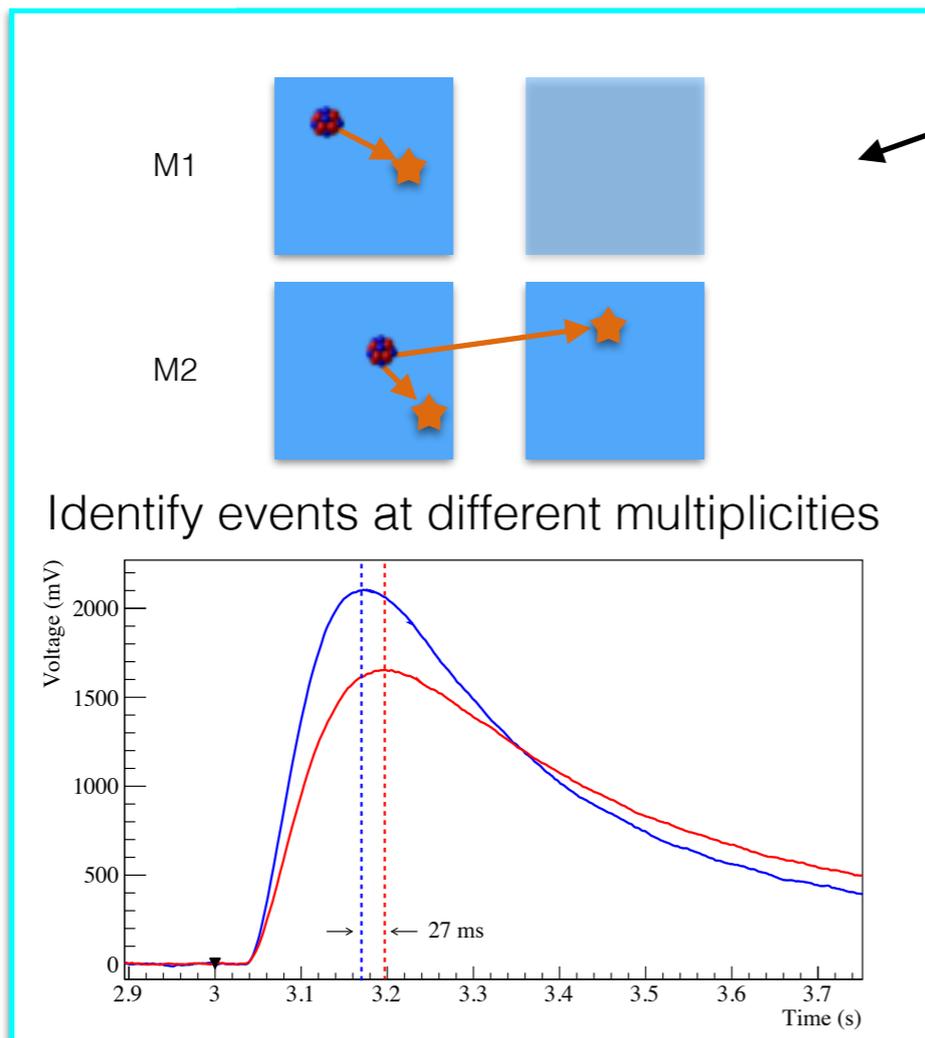
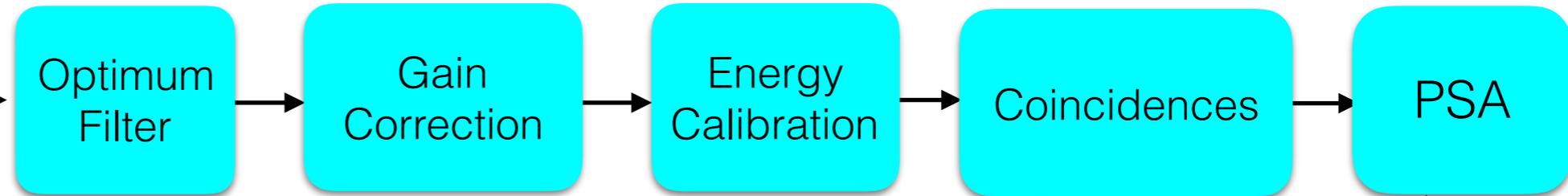
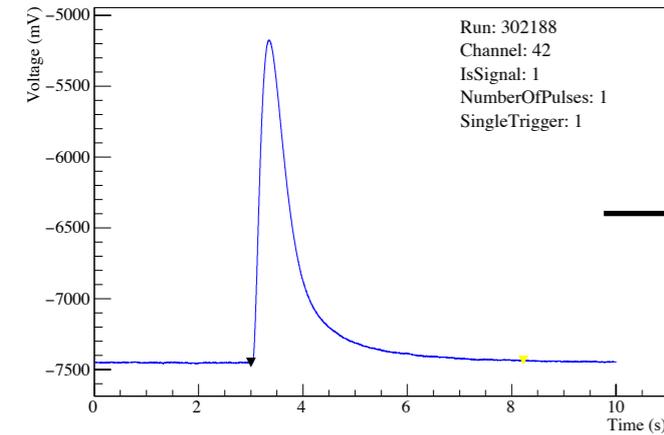
CUORE data-processing



Calibration system:
 $^{232}\text{Th} + ^{60}\text{Co}$ sources
 8 strings positioned in
 between the 300K
 vessel and the
 external Lead Shield



CUORE data-processing

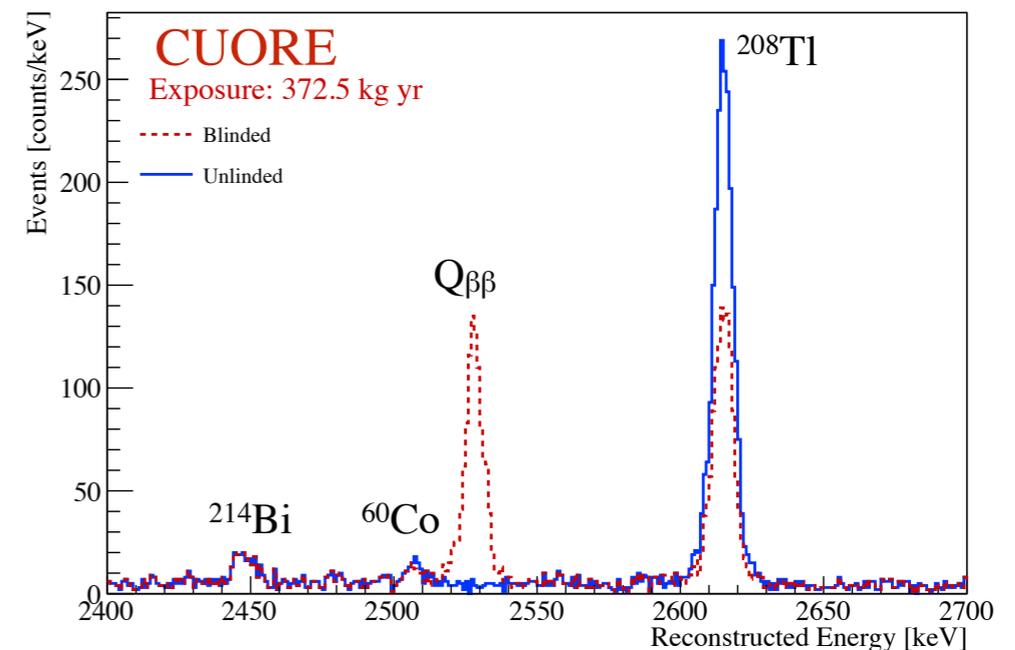


$0\nu\beta\beta$ decay search

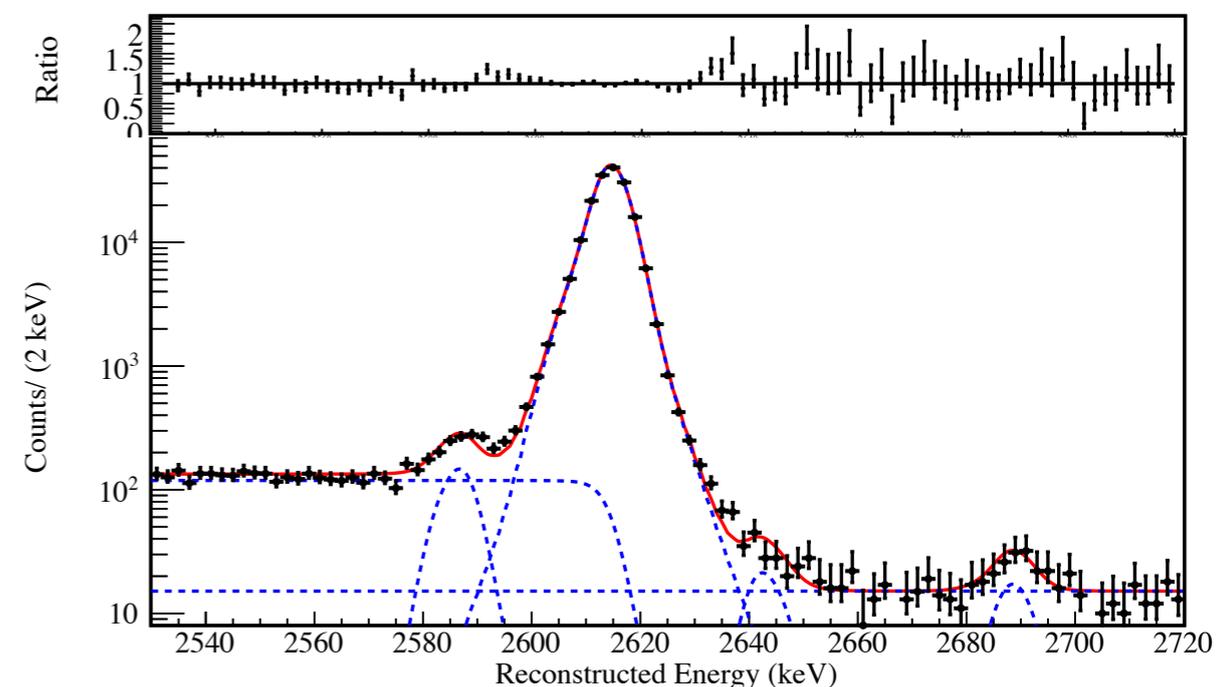
Total exposure for $0\nu\beta\beta$ decay search (PRL-2020)
372.5 kg yr $^{\text{nat}}\text{TeO}_2$, ^{130}Te exposure: 103.6 kg yr

(After analysis selections)

- **Blinding of the background spectrum:** optimization of analysis procedures and selections
- Event selection is performed after discarding periods of low quality data (about 1% of live time)
- Detector response function built on the 2615 keV calibration line. Apply a scaling factor to obtain the correct **energy resolution at $Q_{\beta\beta}$: (7.0 ± 0.4) keV FWHM**
- Containment efficiency for a $0\nu\beta\beta$ decay to be single site event (evaluated via MC) - $(88.350 \pm 0.090)\%$
- Selection efficiencies (evaluated on data): trigger, energy reconstruction, pile-up rejection, multiplicity (M1), PSA - $(87.54 \pm 0.17)\%$



Combined Calibration Fit (DS 2)



$0\nu\beta\beta$ decay search

$0\nu\beta\beta$ peak search

Unblinded data:

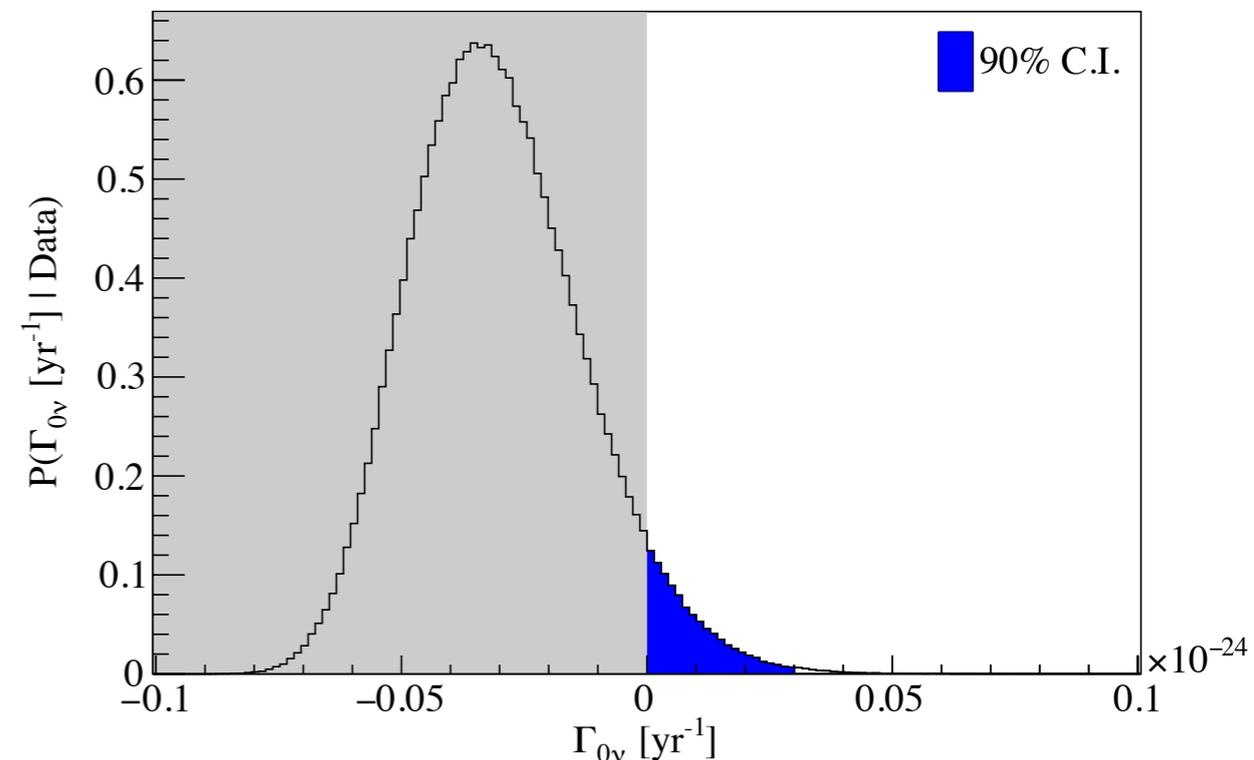
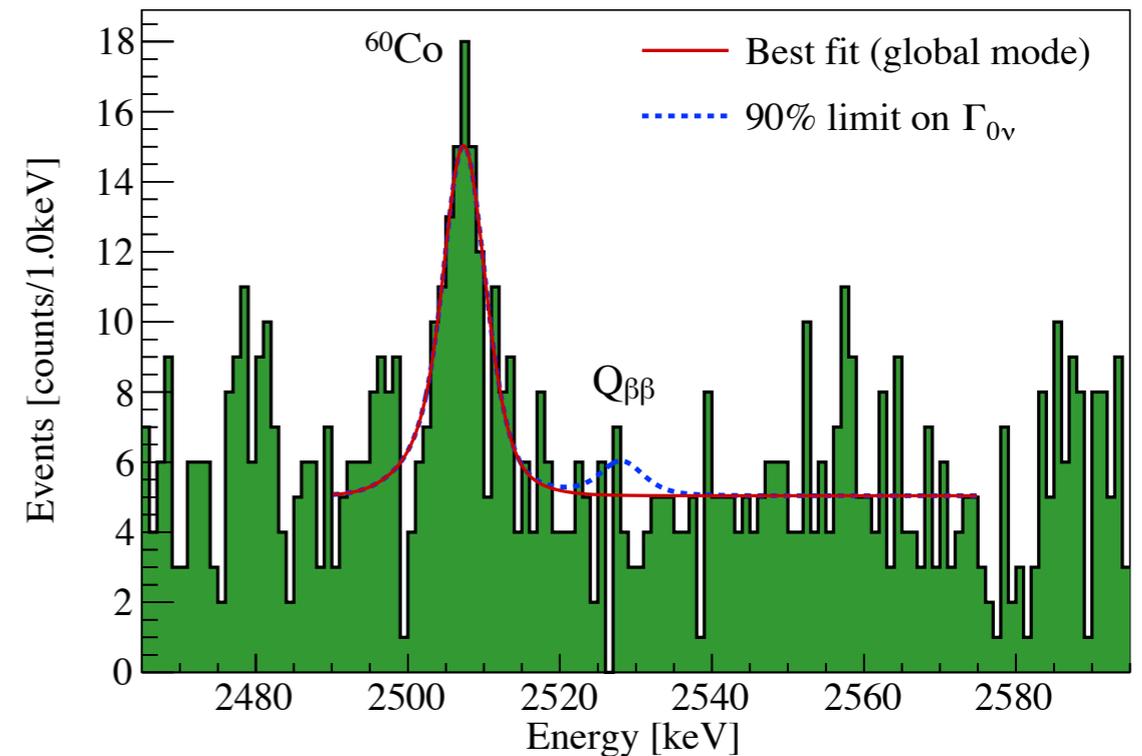
- Bayesian Analysis (BAT)
- Likelihood model: flat continuum (BI), posited peak for $0\nu\beta\beta$ (rate), peak for ^{60}Co (rate + position)
- Unbinned fit in ROI [2490,2575 keV] on physical range (rates non-negative), uniform prior on $\Gamma_{0\nu}$
- Systematics: repeat fits with nuisance parameters, allow negative rates (<0.4% impact on limit)

No evidence of signal.

Posterior of $\Gamma_{0\nu}$: extract an upper limit on decay rate.

Half-life limit for $0\nu\beta\beta$ in ^{130}Te (PRL-2020)

$T_{0\nu}^{1/2} (^{130}\text{Te}) > 3.2 \times 10^{25}$ yr (90%C.I including syst.)



$0\nu\beta\beta$ decay search

Repeating the fit in the ROI, without the $0\nu\beta\beta$ decay contribution

ROI background index (B) = $(1.38 \pm 0.07) \times 10^{-2} \text{ c}/(\text{keV}\cdot\text{kg}\cdot\text{yr})$

Exclusion sensitivity for $0\nu\beta\beta$ decay:

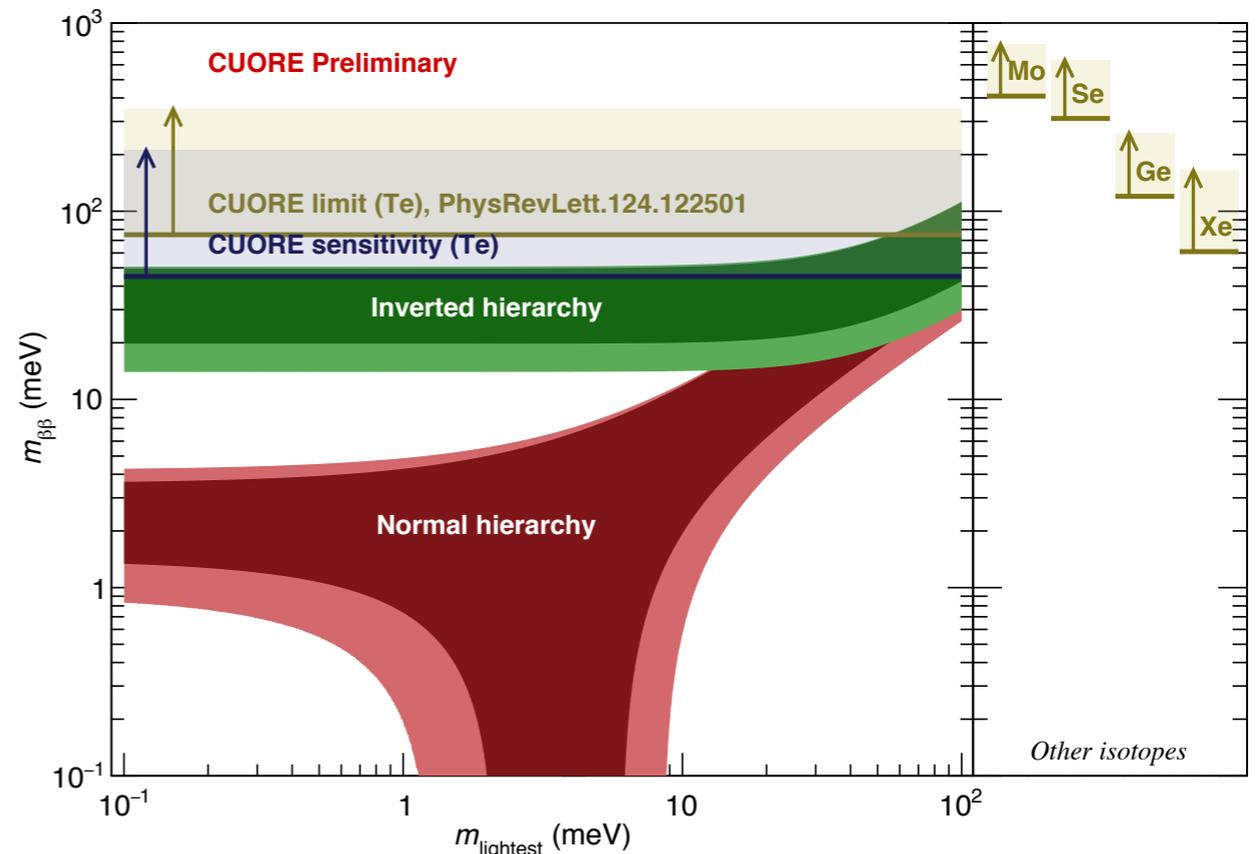
Generate pseudo-experiments with bkg-only hypothesis, fit the ROI with bkg+signal hypothesis

CUORE median exclusion sensitivity on ^{130}Te half-life: $T_{0\nu}^{1/2} (^{130}\text{Te}) = 1.7 \times 10^{25} \text{ yr}$

Probability to get a more stringent limit given the current sensitivity: 3.2%.

Limit on $0\nu\beta\beta$ decay half life and interpretation in context of light Majorana neutrino exchange:

$m_{\beta\beta} < 75 - 350 \text{ meV}$ at 90% C.I. (PRL-2020)



 Alduino C. et al. (CUORE collaboration), Phys. Rev. Lett. 124, 122501, (2020), <https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.124.122501>

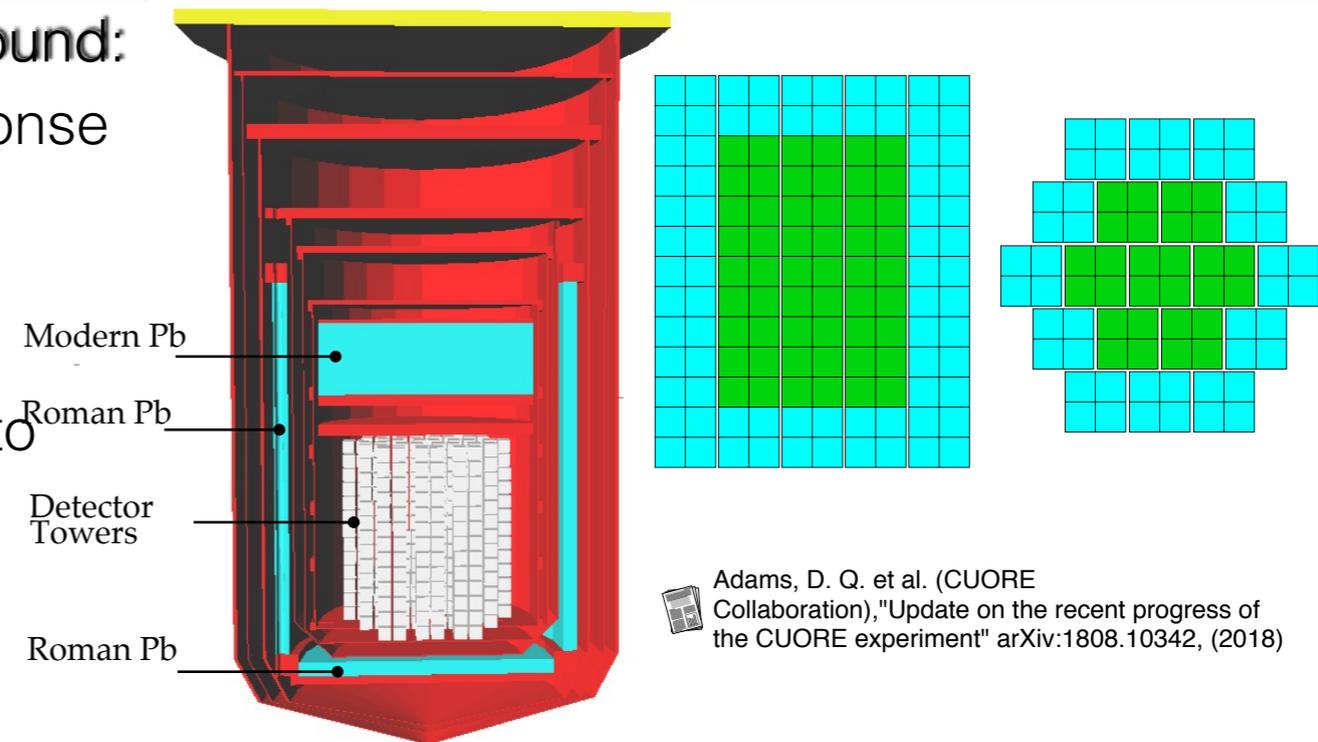
2νββ decay and background analysis

Reconstruction of the CUORE continuum background:

- GEANT4 simulation + measured detector response function to produce expected spectra
- 61 background sources simulated, bayesian MCMC fit with uniform priors (except muons)
- Exploit coincidences & detector self-shielding to constrain location of sources

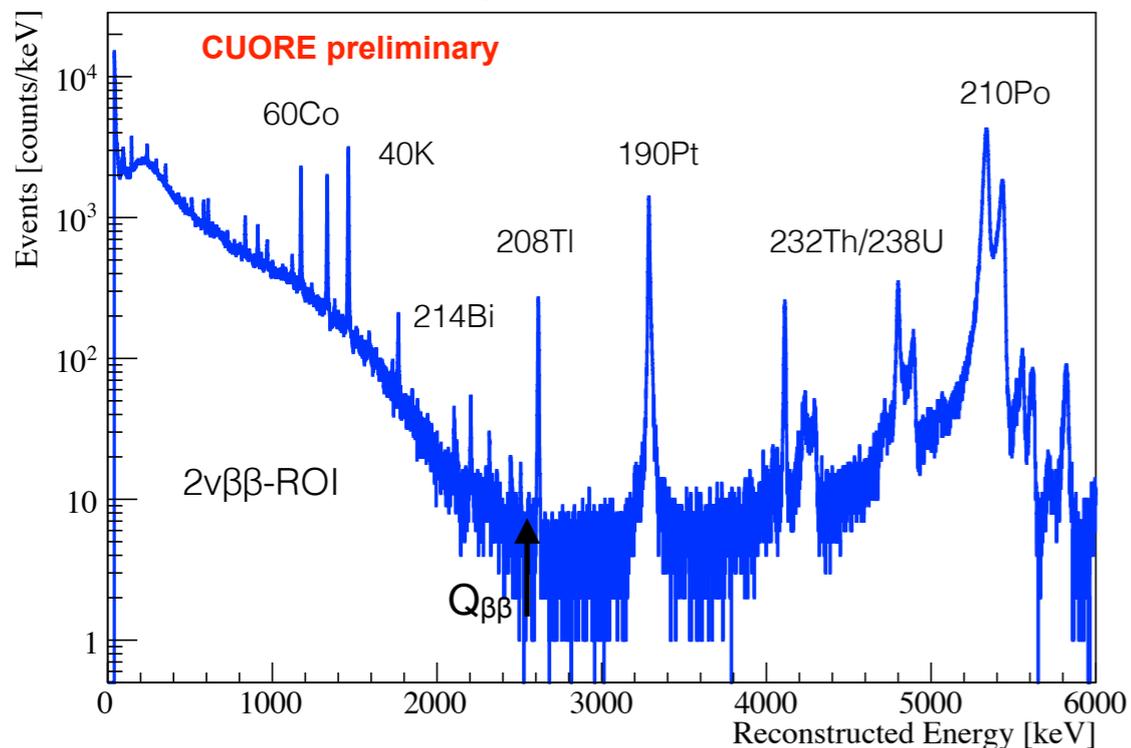
Total exposure for 2νββ analysis: 300.7 kg yr

 "CUORE Results and the CUPID Project" at Neutrino 2020 conference, https://indico.fnal.gov/event/43209/contributions/187866/attachments/129542/159294/CUORE_CUPID_Nu2020.pdf *Paper in preparation*

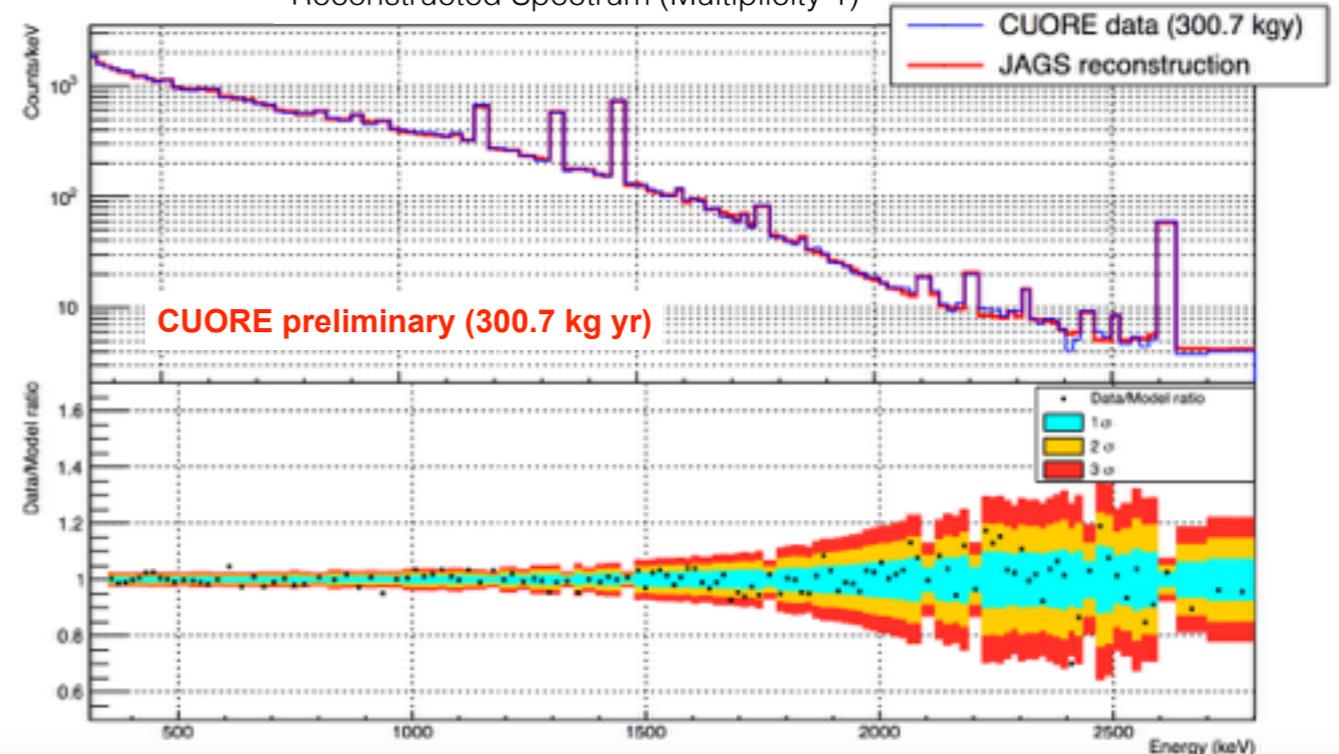


 Adams, D. Q. et al. (CUORE Collaboration), "Update on the recent progress of the CUORE experiment" arXiv:1808.10342, (2018)

Summed background spectrum (Multiplicity 1)



Reconstructed Spectrum (Multiplicity 1)



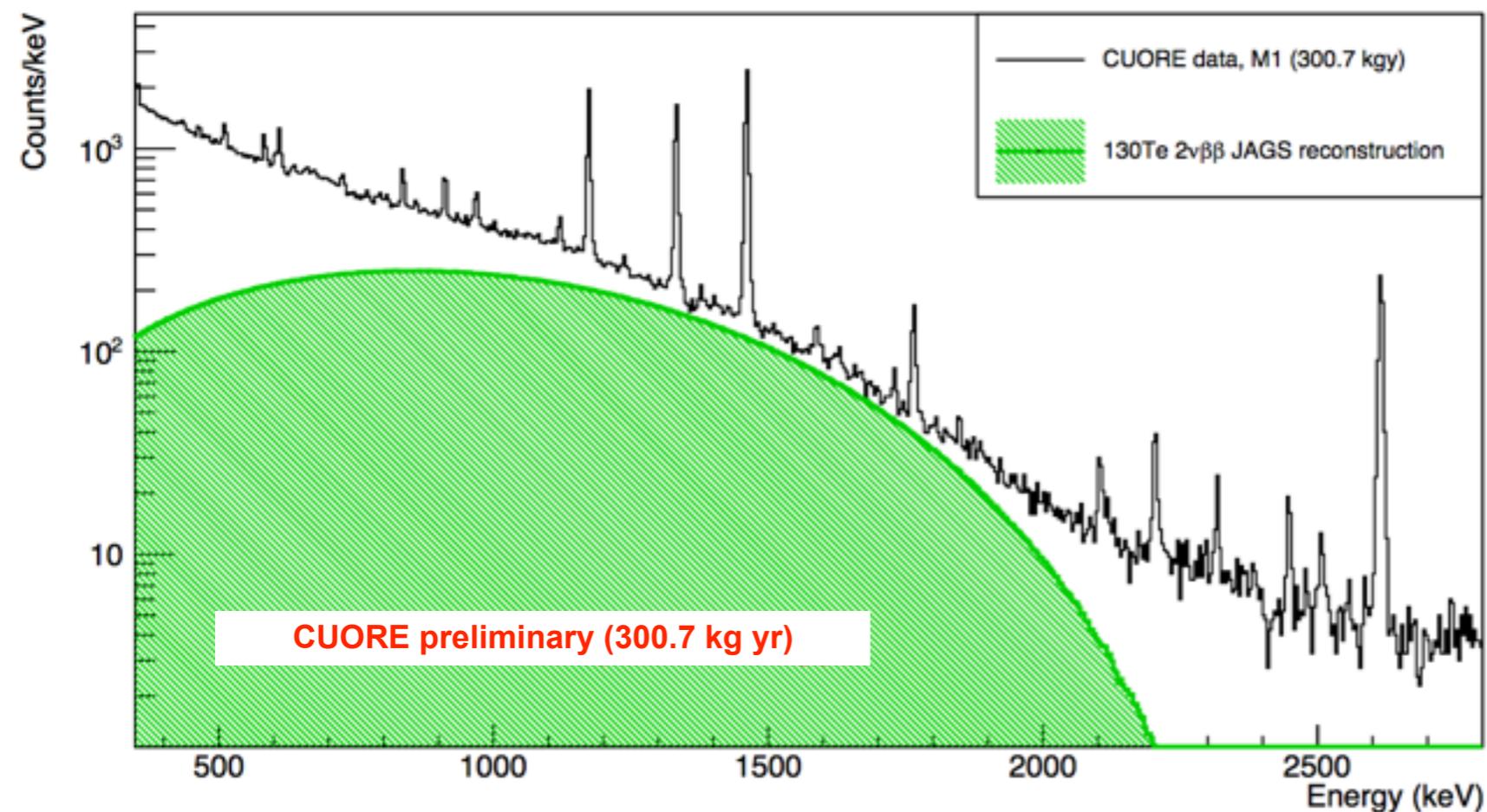
$2\nu\beta\beta$ decay and background analysis

$2\nu\beta\beta$ decay: dominant component of the observed M1 spectrum between ~ 1 to 2 MeV, due to reduced γ backgrounds and self shielding of outer TeO_2 towers

Measurement of the $2\nu\beta\beta$ half-life of ^{130}Te

$$T_{2\nu}^{1/2} (^{130}\text{Te}) = [7.71^{+0.08}_{-0.06}(\text{stat})^{+0.17}_{-0.15}(\text{syst})] \times 10^{20} \text{ yr}$$

^{130}Te $2\nu\beta\beta$ - M1



Systematic uncertainties:

- Data selection: geometric splitting, time splitting, fit range
- Choice of $2\nu\beta\beta$ spectrum (SSD vs HSD)
- Unconstrained fallout products (^{90}Sr)

$\beta\beta$ decay to excited states analysis

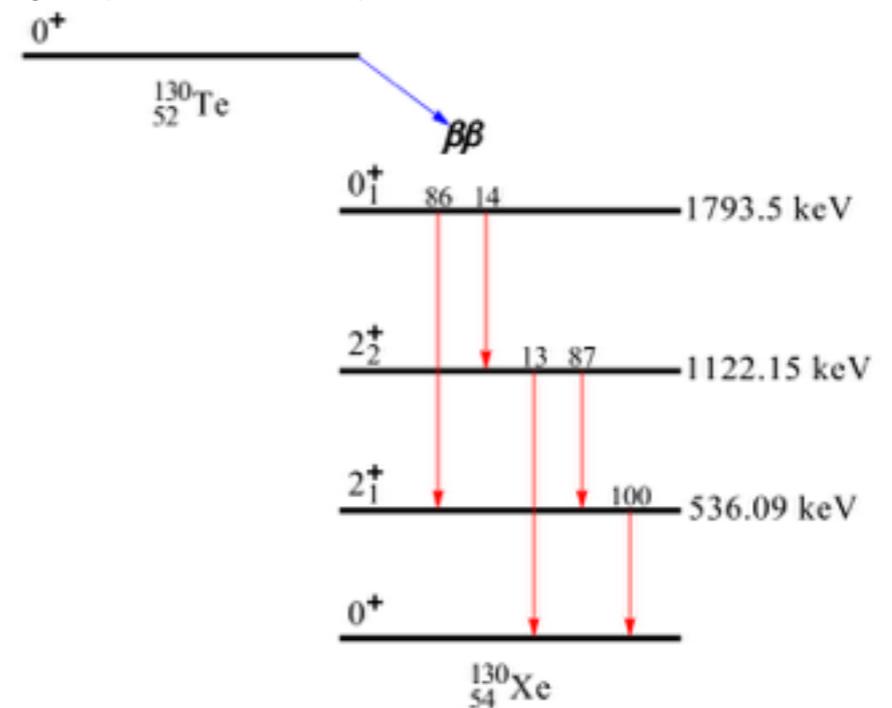
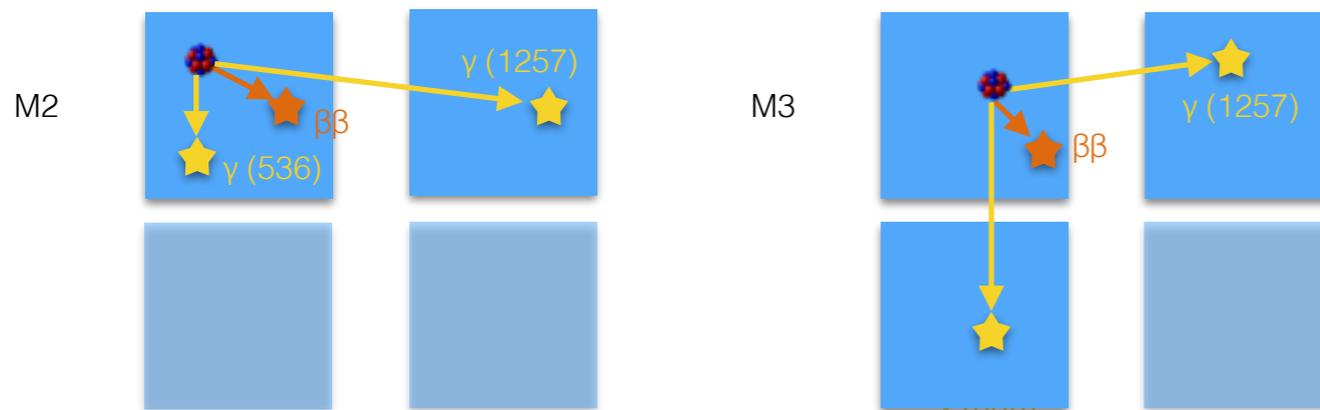
Search for $0\nu\beta\beta$ and $2\nu\beta\beta$ decays of ^{130}Te to the first 0^+ excited state of ^{130}Xe

- Double beta decay can proceed also through transitions to the various excited states of the daughter nucleus
- $2\nu\beta\beta$ decay to the 0^+ excited state observed in ^{100}Mo and ^{150}Nd , with half lives of the order of few 10^{20} yr
- Previous attempts of measuring the $\beta\beta$ decay of ^{130}Te to the first 0^+ excited state of ^{130}Xe made by both CUORICINO and CUORE-0:
 $(T^{1/2})^{0\nu_{0^+}} > 1.4 \times 10^{24}$ yr (90% C.L.), $(T^{1/2})^{2\nu_{0^+}} > 2.5 \times 10^{23}$ yr (90% C.L.)

Signature of the decay:

Cascade of de-excitation γ s in coincidence with $\beta\beta$ s

- multi-site signatures
- background reduction with respect to the corresponding transitions to the ground state, especially in case of a high detector granularity



Pattern	BR [%]	Energy γ_1	Energy γ_2	Energy γ_3
A	86%	1257 keV	536 keV	-
B	12%	671 keV	586 keV	536 keV
C	2%	1122 keV	671 keV	-

$\beta\beta$ decay to excited states analysis



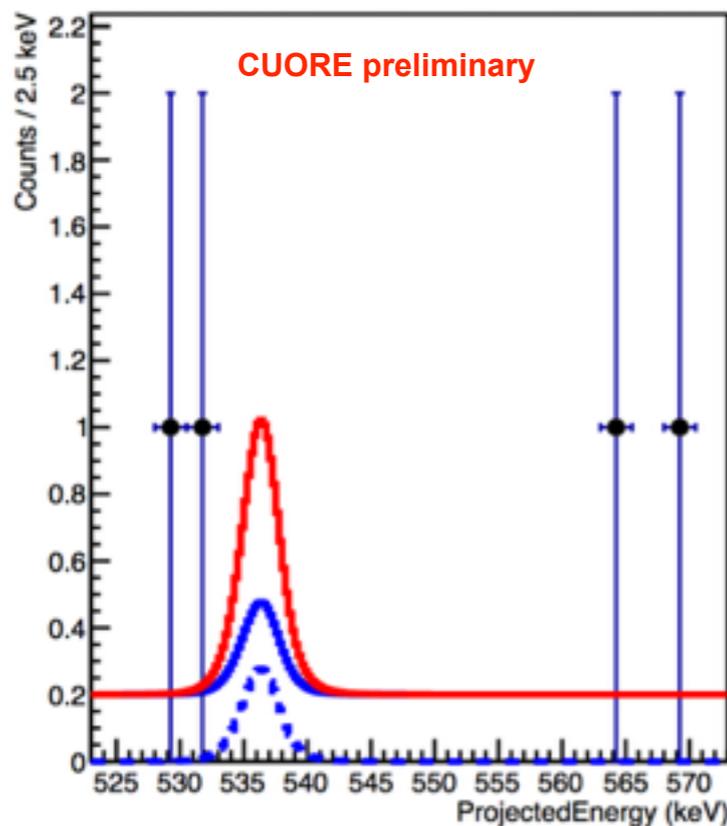
Considering only fully contained events for the analysis

Experimental signatures considered for the analysis:

- 2A0-2B1: Multiplicity 2, crystal1 = $\beta\beta + \gamma(536)$ & crystal2 = $\gamma(1257)$
- 2A2-2B3: Multiplicity 2, crystal1 = $\gamma(536)$ & crystal2 = $\beta\beta + \gamma(1257)$
- 3A0: Multiplicity 3, crystal1 = $\beta\beta$ & crystal2 = $\gamma(536)$ & crystal3 = $\gamma(1257)$

These are the signatures which contribute the most to the discovery sensitivity in the $\beta\beta$ decay rate

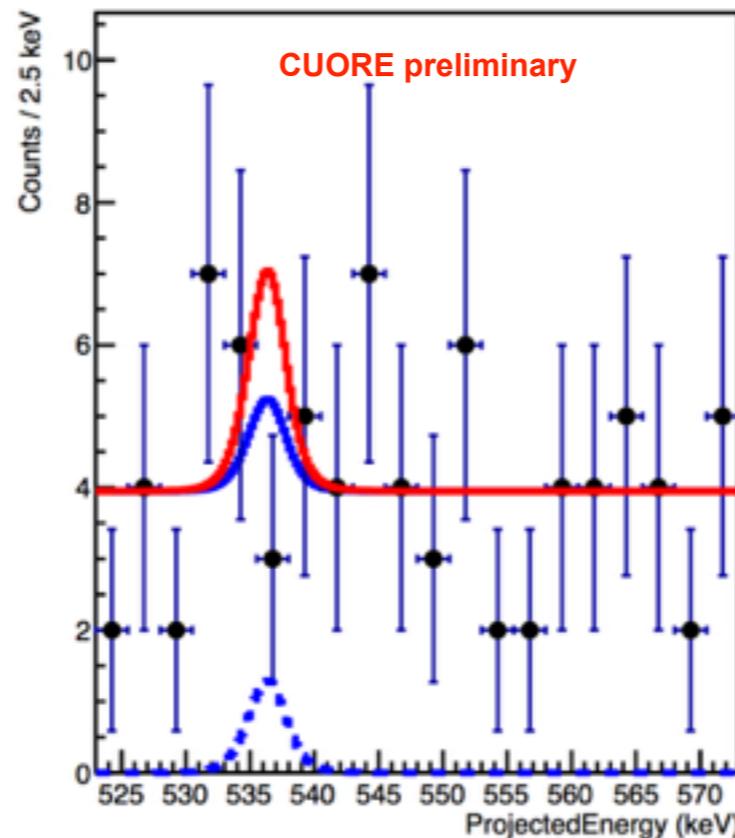
$0\nu\beta\beta$, sig. 2A2-2B3



crystal1 ~ E in[523, 573], γ (536)

crystal2 ~ E in[1981, 2001], $\beta\beta$ (734) + γ (1257)

$2\nu\beta\beta$, sig. 2A2-2B3



crystal1 ~ E in[523, 573], γ (536)

crystal2 ~ E in[1360, 1990], $\beta\beta$ (0-734) + γ (1257)

No evidence of signal for both $0\nu\beta\beta$ and $2\nu\beta\beta$ decays of ^{130}Te to ^{130}Xe 0^+ excited state

$0\nu\beta\beta$:
 $(T^{1/2})^{0\nu 0^+} > 5.9 \times 10^{24}$ yr (90% C.I.)

$2\nu\beta\beta$:
 $(T^{1/2})^{2\nu 0^+} > 1.3 \times 10^{24}$ yr (90% C.I.)

"CUORE Results and the CUPID Project" at Neutrino 2020 conference, https://indico.fnal.gov/event/43209/contributions/187866/attachments/129542/159294/CUORE_CUPID_Nu2020.pdf

Paper in preparation

Other physics analyses



The CUORE experiment has the potential for the search for rare events and/or for physics beyond the Standard Model other than the $0\nu\beta\beta/2\nu\beta\beta$ decay of ^{130}Te

- Rare decays:
 - $0\nu\beta\beta/2\nu\beta\beta$ decay of $^{128}\text{Te} \rightarrow ^{128}\text{Te}$: $Q_{\beta\beta} = 865.87$ keV, natural abundance: 31.74%
 - $0\nu(\beta+\text{EC})$ ^{120}Te decay $\rightarrow ^{120}\text{Te}$: $Q_{\beta\beta} = 1714.8$ keV, natural abundance: 0.09%, clear signature
 - ...
- Low energy studies: dark matter - WIMP, axions, ...
- Spectral shape studies:
 - $0\nu\beta\beta/2\nu\beta\beta$ decay with Majoron emission,
 - CPT violation in $2\nu\beta\beta$ decay,
 - ...

CUORE $0\nu\beta\beta$ sensitivity



CUORE main analysis - $0\nu\beta\beta$ decay search

$0\nu\beta\beta$ decay exclusion sensitivity in 5 years (90% C.L.):

$S_{0\nu} \sim 9 \times 10^{25}$ yr, $m_{\beta\beta} < 50\text{-}130$ meV

with

nominal background **B**: 10^{-2} c/(keV·kg·yr)

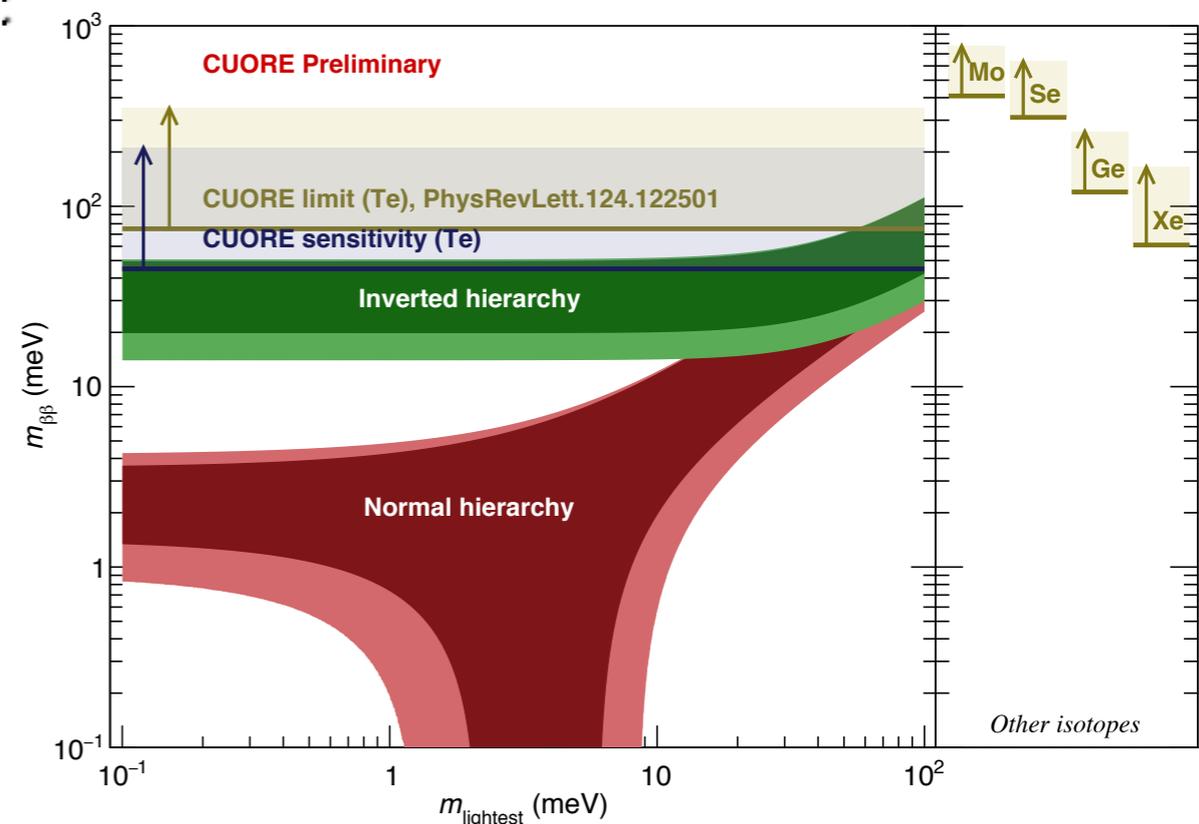
and

nominal energy resolution: **5 keV FWHM**

in the Region Of Interest (ROI)

CUORE TeO_2 detectors background:

- Degraded α particles, produced from radioactive decays close to the detectors or on their surface, which deposit part of their energy in the detectors, constitute the main ($\sim 90\%$) contribution to the CUORE background index in the ROI.
- Multi-Compton of γ emitted by the $^{232}\text{Th}/^{238}\text{U}$ chains and cosmic muons, constitute the remaining background contribution



CUORE, what's next?

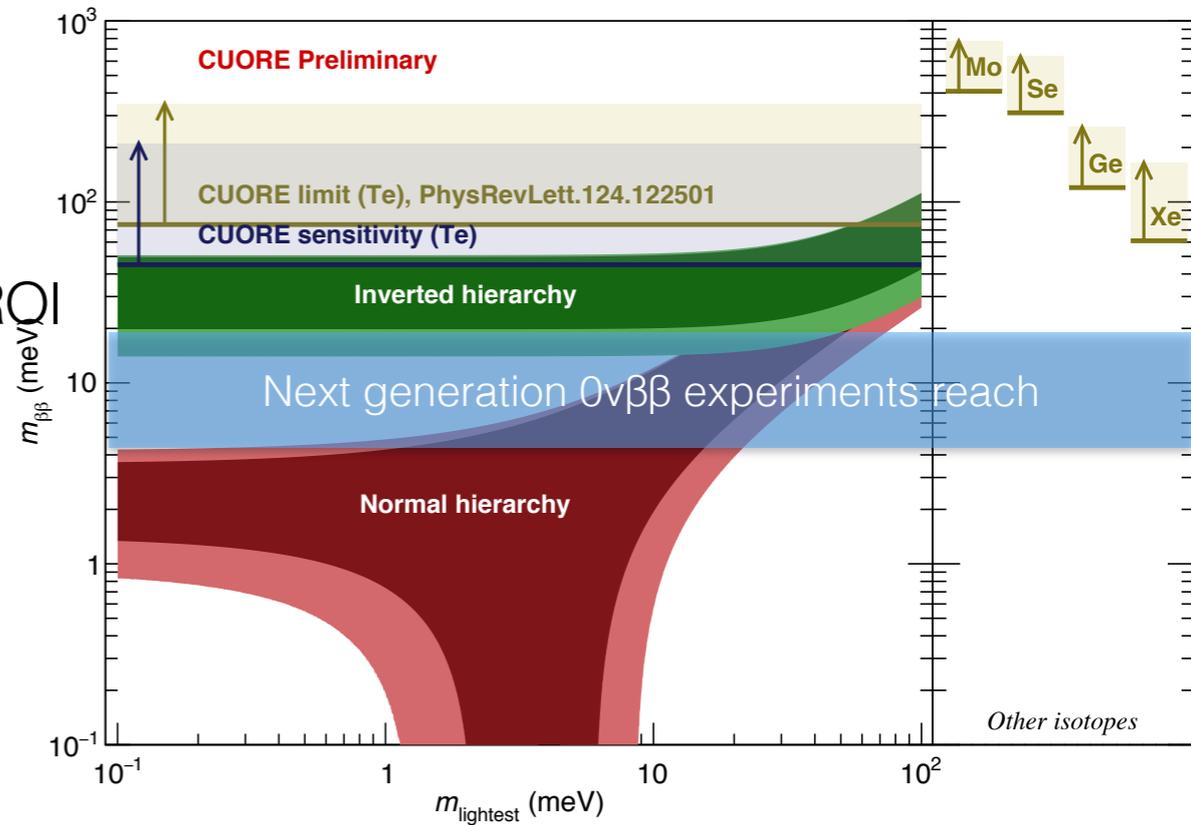
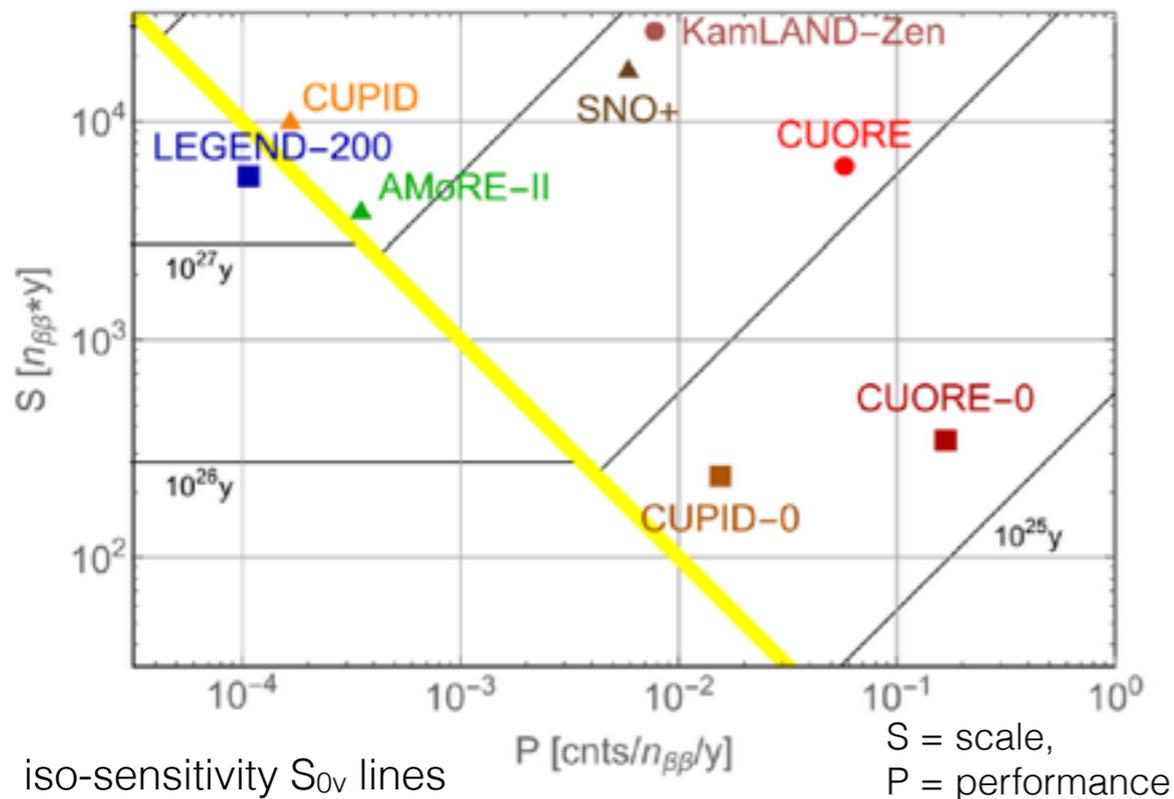


Next generation of $0\nu\beta\beta$ decay experiments seek to be sensitive to the full Inverted Hierarchy region:

Sensitivity $S_{0\nu} \sim 10^{27}$ yr, $m_{\beta\beta} \sim 6 - 20$ meV

To reach these sensitivities:

- Reach the 'zero background' regime: lower the background (and improve energy resolution) in the ROI
- Larger active masses



M. Biassoni and O. Cremonesi, Progr. Part. Nucl. Phys. Vol. 114, 103803 (2020)
<https://doi.org/10.1016/j.pnpnp.2020.103803>

CUORE, what's next? CUPID

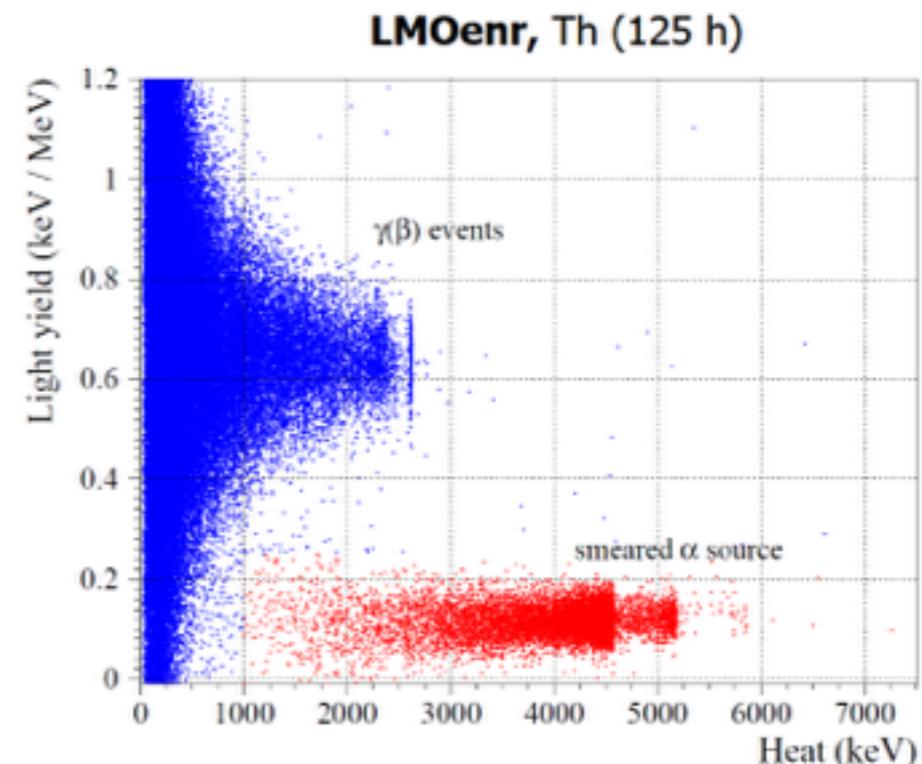
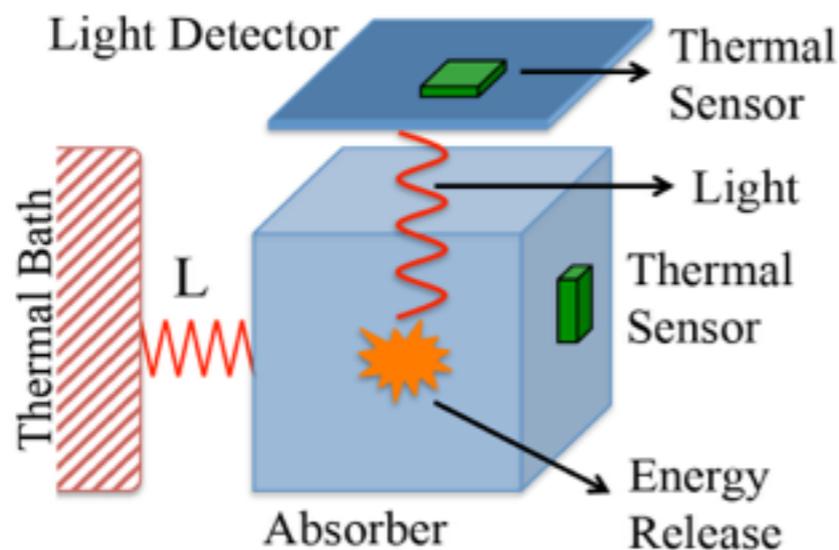
Next generation of $0\nu\beta\beta$ decay experiments with cryogenic calorimeters

- CUORE is an ideal calorimeter. TeO_2 detectors measure only heat \rightarrow no discrimination of α vs β/γ events in the ROI.
- Need for hybrid approaches to discriminate/reduce the α contribution in the ROI. Use other $\beta\beta$ candidates (^{48}Ca , ^{82}Se , ^{100}Mo) with high $Q_{\beta\beta}$ and/or scintillating compounds

CUPID (CUORE Upgrade with Particle IDentification)

$\text{Li}_2^{100}\text{MoO}_4$ scintillating crystals (CUPID-Mo, successful proof of concept)

- ▶ readout of both heat and scintillation light with thermal sensors
- ▶ alpha-particle rejection using light signal
- ▶ ^{100}Mo $\beta\beta$ decay candidate: $Q_{\beta\beta} \sim 3034$ keV



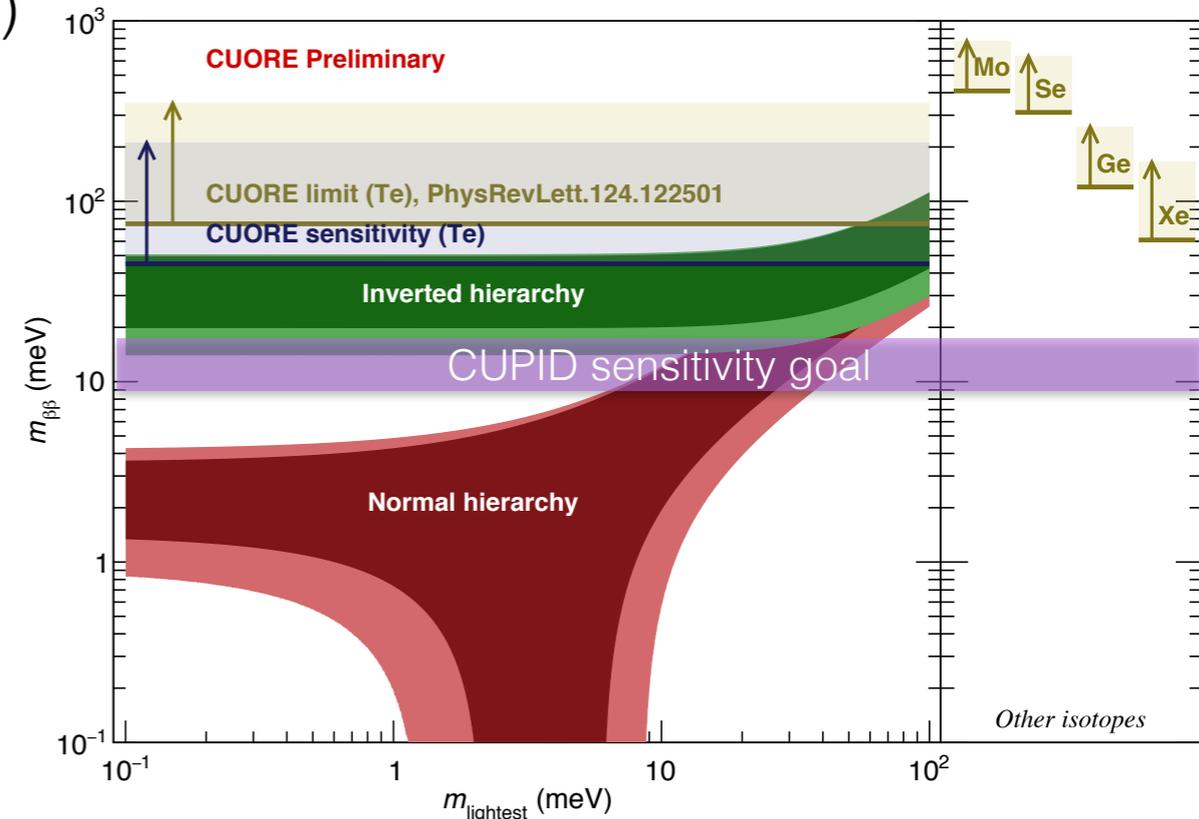
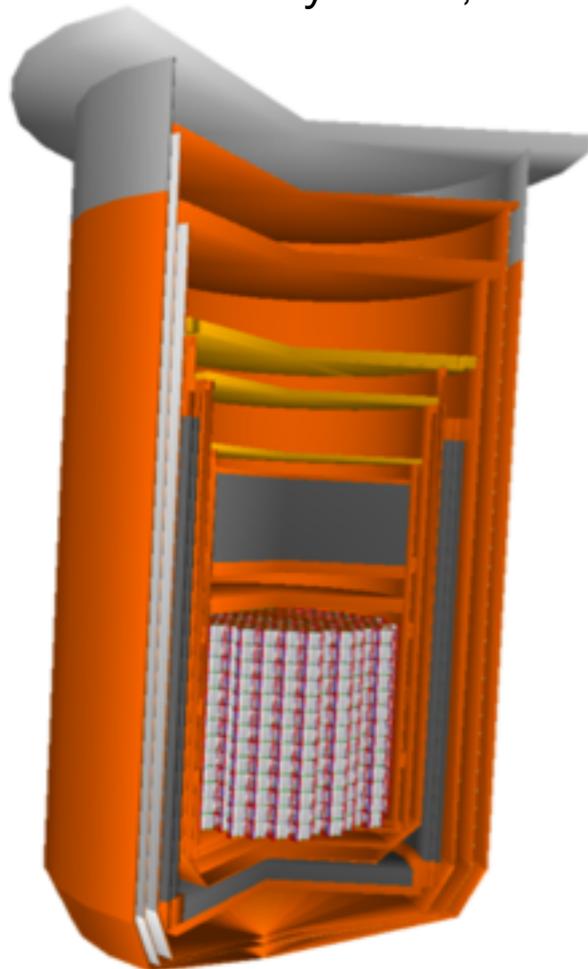
CUORE, what's next? CUPID



CUPID: 1 tonne of scintillating LiMoO_4 detectors

- ~1500 scintillating Li_2MoO_4 calorimeters, each cubic crystal ~ 300g
- Crystals enriched > 95% in ^{100}Mo (~250 kg of ^{100}Mo)
- Li_2MoO_4 crystals are facing Ge light detectors; both are read via NTD thermistors
- The CUPID detector will be hosted in the CUORE cryostat, at the end of CUORE data-taking

CUPID_pre-CDR - arXiv:1907.09376



Background goal:

$B < 10^{-4} \text{ c}/(\text{keV}\cdot\text{kg}\cdot\text{yr})$ nella ROI

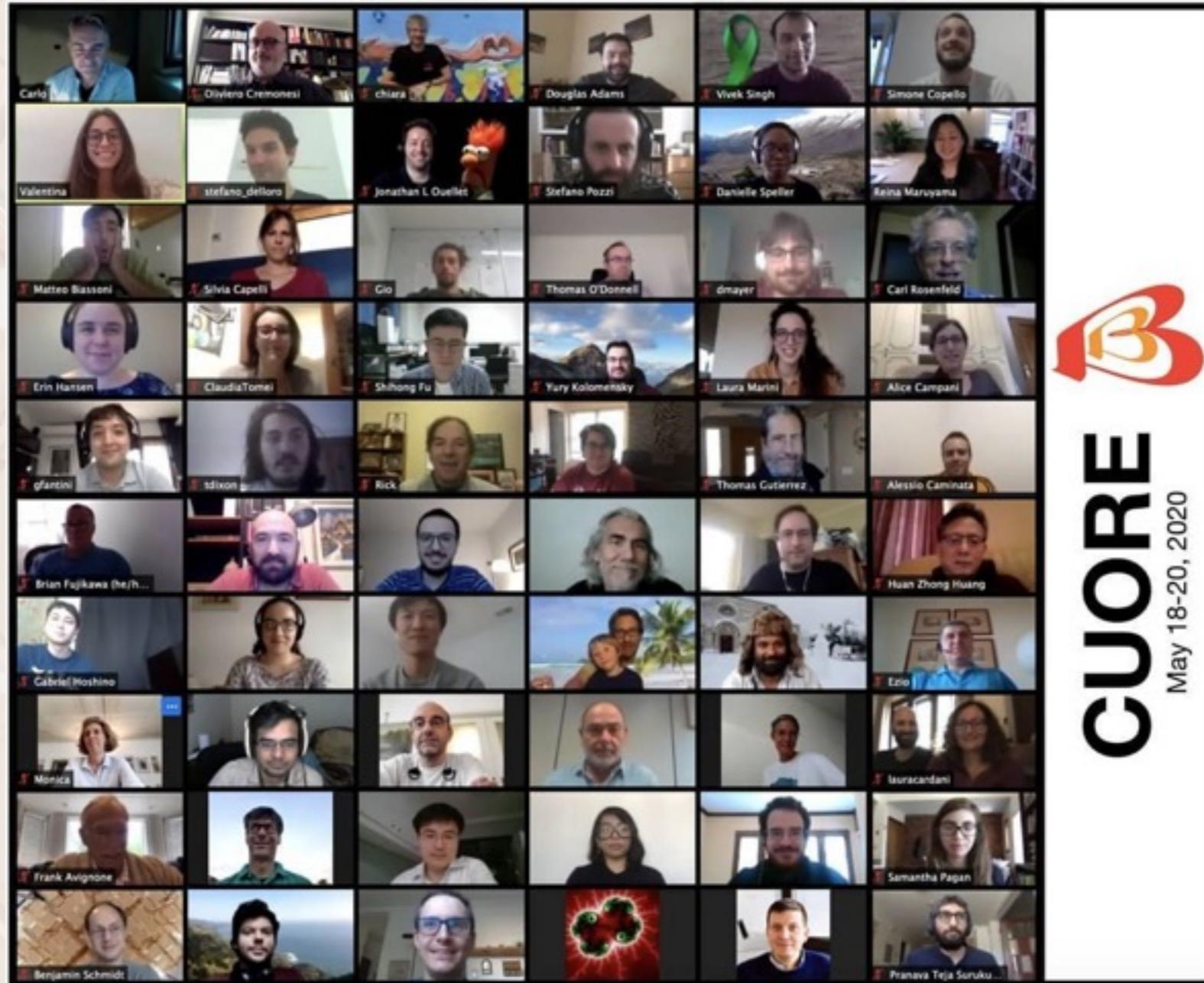
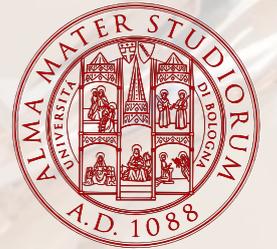
- Particle ID (α vs β/γ) with scintillation
- Possible discrimination of $2\nu\beta\beta$ pile-up from pulse-shape
- Background reduction: underground location at LNGS, passive shields (Pb/Cu), high-radiopurity in assembly and storage of detectors and materials, muon veto, profit of detector high granularity

Conclusion



- CUORE demonstrates the feasibility of a tonne-scale experiment employing cryogenic calorimeters, for the search of the $0\nu\beta\beta$ decay
- Low temperature detectors technology competitive with other techniques in terms of performance (energy resolution, background reduction ...) and scalability, reaching similar sensitivities for $0\nu\beta\beta$ decay search.
- CUORE released physics results of ^{130}Te $0\nu\beta\beta$ and $2\nu\beta\beta$ decays to ground and excited states with the physics data collected in 2017-2019
- A raw exposure of ~ 1 tonne yr has been achieved and data-taking is proceeding. Updated results on $0\nu\beta\beta$ and other new analyses will be released soon!
- The CUORE data taking is currently underway to collect 5 years of run time
- Important feedback from CUORE operations for the future CUPID project (CUORE Upgrade with Particle Identification)

Thank you on behalf of the CUORE collaboration



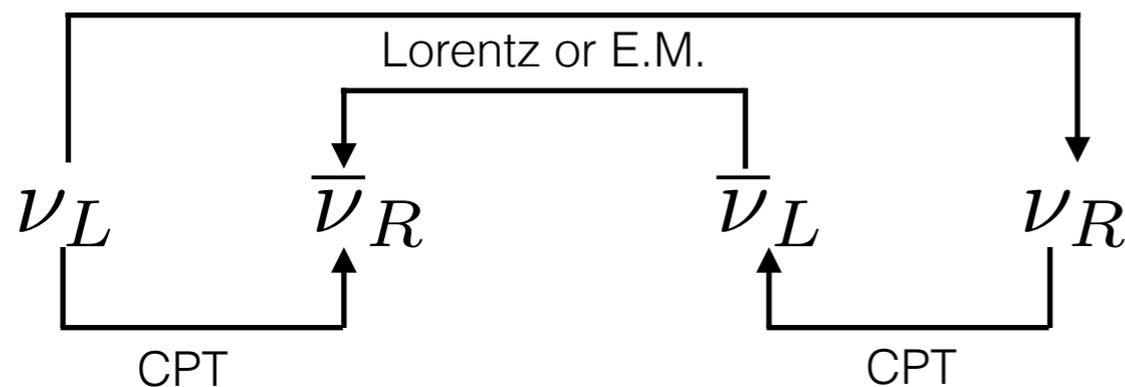
CUORE
May 18-20, 2020

Backup

Neutrino mass nature: Dirac or Majorana

- Minimal Standard Model: massless neutrinos
- Massive ν : distinction between Dirac and Majorana descriptions

Dirac



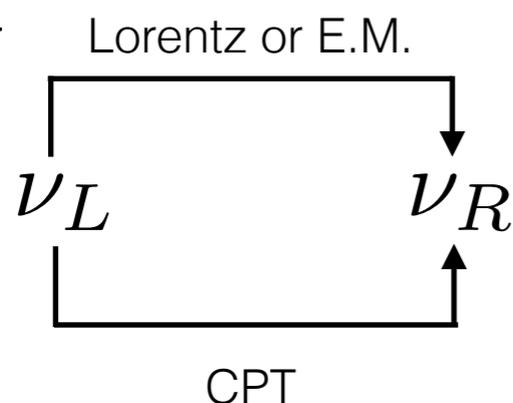
Dirac neutrino:

- 4 ν states with same mass
- Impose the lepton number conservation
- Yukawa coupling with Higgs doublet
- degenerate states
- ν_L active, ν_R sterile

$$\mathcal{L}_{mass,\nu}^D = m_D (\bar{\nu}_L \nu_R + h.c.)$$

where $m_\nu = y_\nu v$

Majorana



Majorana neutrino:

Neutrinos are charge-less (apart from L), a neutrino could be its own anti-particle: $\nu_i = \bar{\nu}_i$

- 2 ν states with same mass
- Lepton number violating mass term

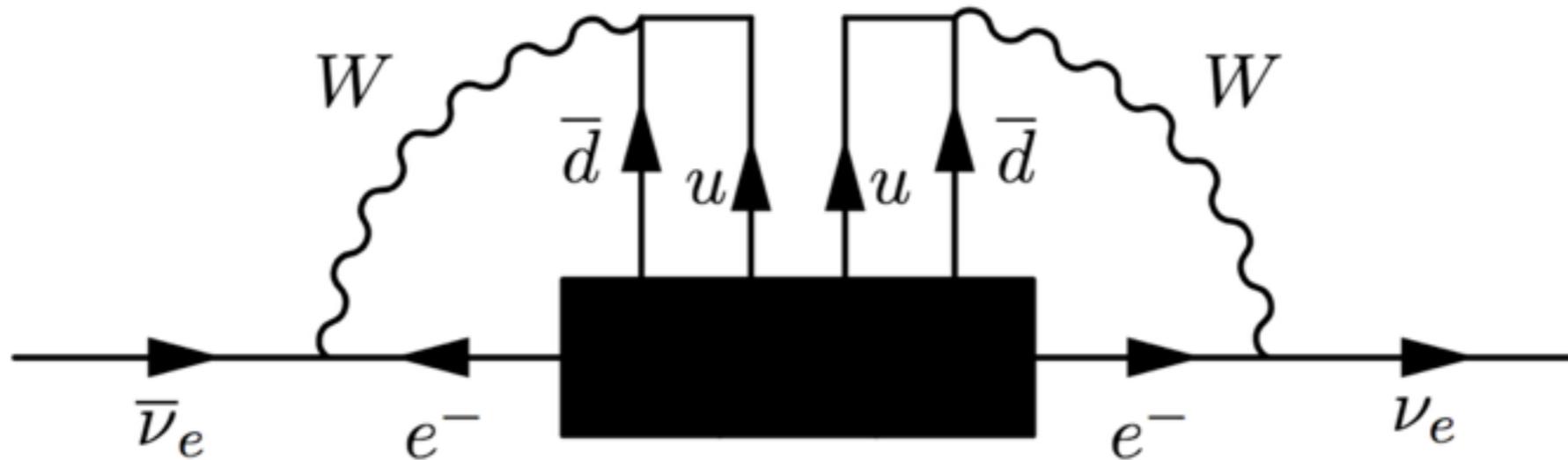
$$\mathcal{L}_{mass,\nu}^M = m_\nu \bar{\nu}_L \nu_L^c$$

See-Saw: Recover 4 nu states

- Light active neutrinos ν_i
- Heavy sterile partners N_i

Neutrinoless double beta decay

The observation of $0\nu\beta\beta$ decay would demonstrate the violation of lepton number and it implies a finite Majorana mass term for neutrinos



Schechter-Valle (Black Box) theorem

Neutrinoless double beta decay

From $0\nu\beta\beta$ decay rate measurements one can infer the effective neutrino mass term

$0\nu\beta\beta$ favorite mechanism:
Light Majorana neutrino exchange

$$\frac{1}{T_{1/2}^{0\nu}} \propto G(Q_{\beta\beta}, Z) |M_{nucl}|^2 |m_{\beta\beta}|^2$$

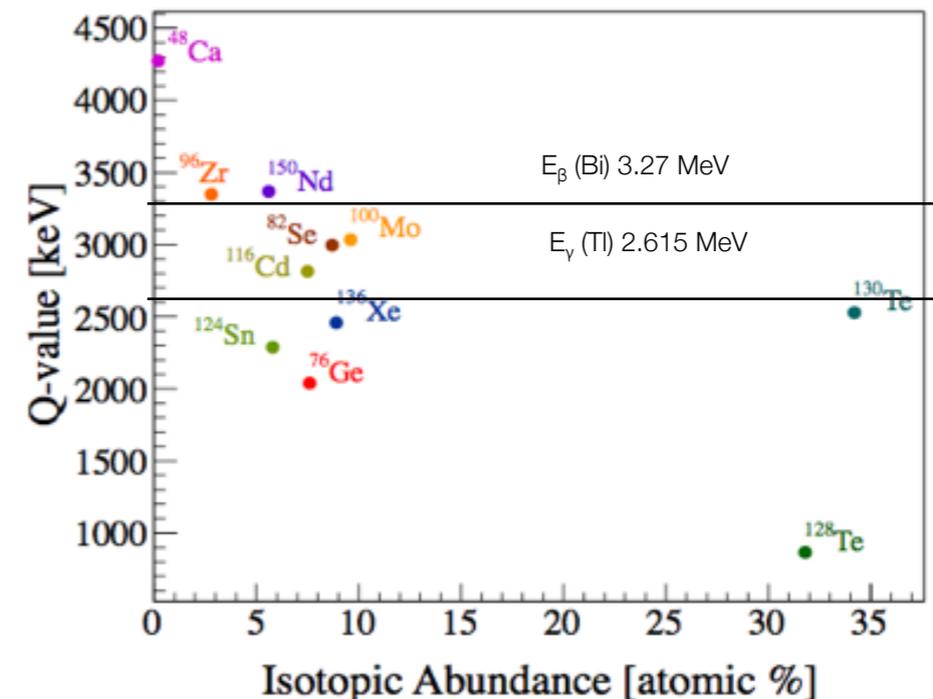
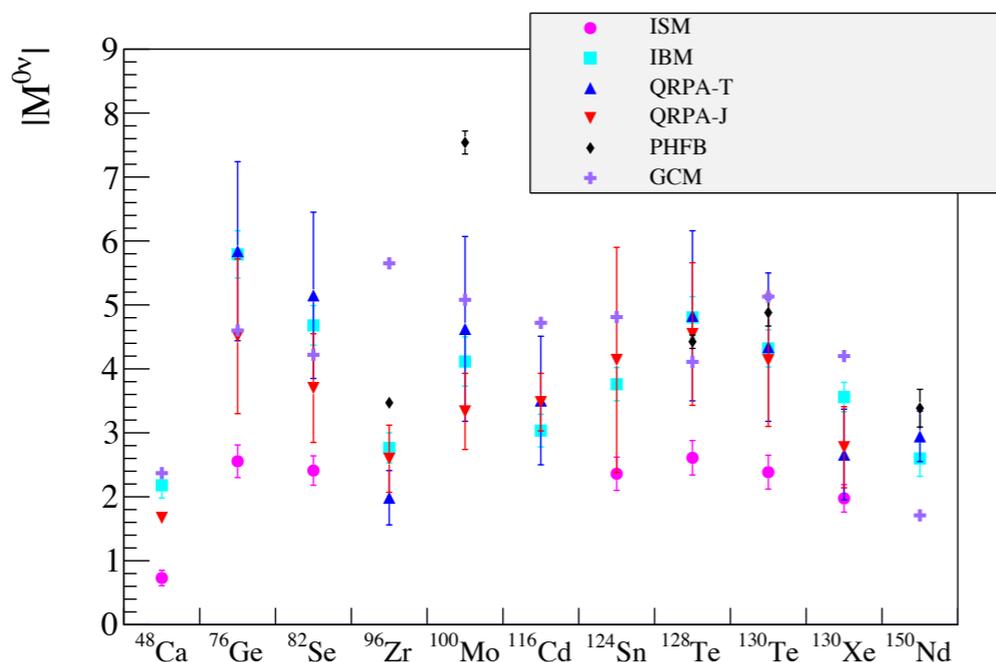
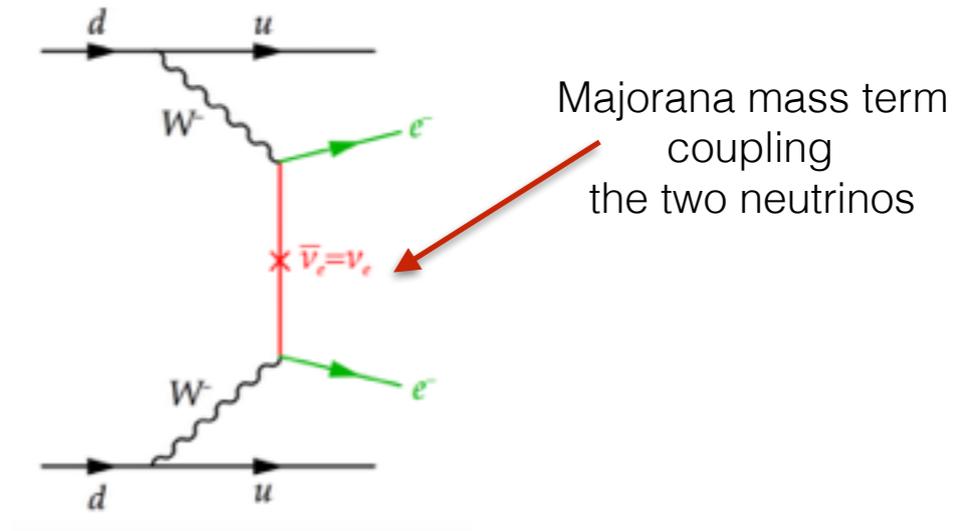
Phase space integral

$$G(Q_{\beta\beta}, Z) \sim Q_{\beta\beta}^5$$

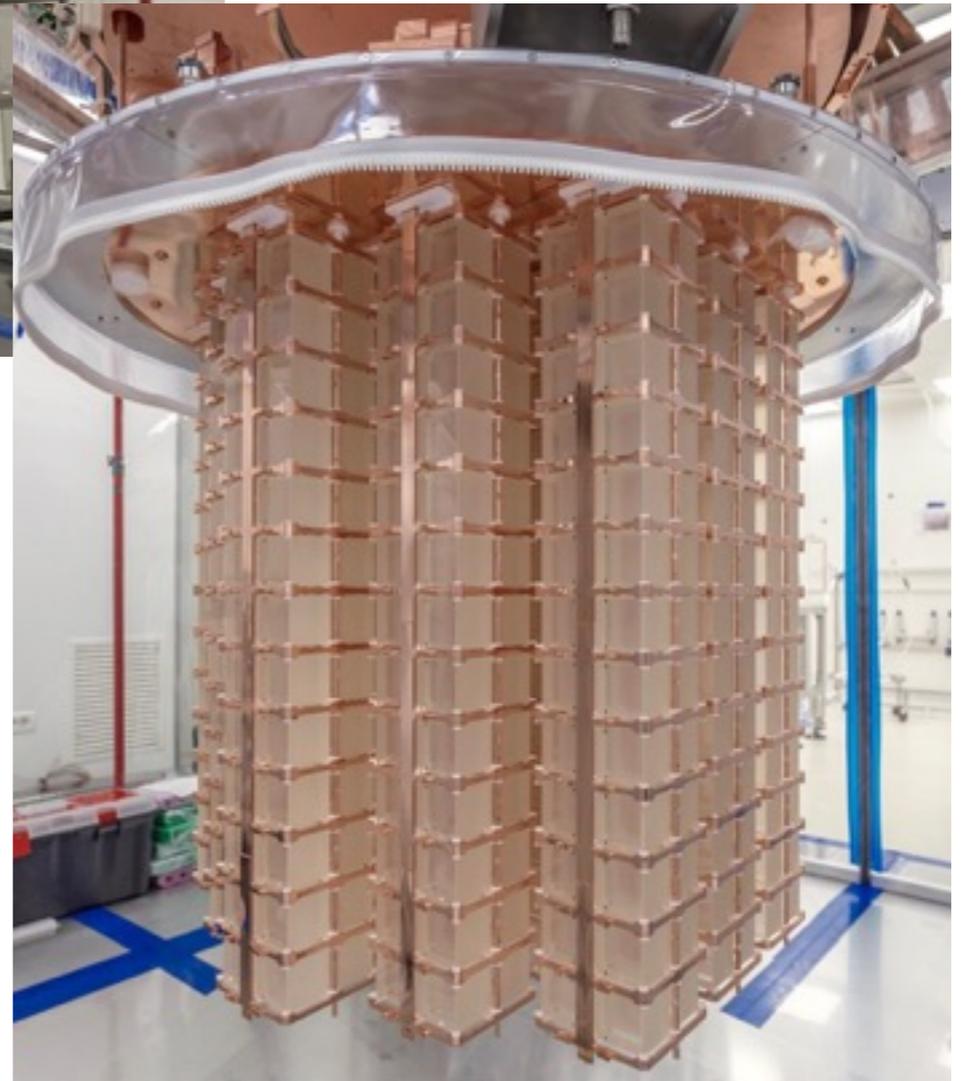
Nuclear matrix element (NME)

Effective neutrino mass term

$$m_{\beta\beta} \equiv \left| \sum_i m_{\nu_i} U_{ei}^2 \right| = \left| e^{i\alpha_1} |U_{e1}^2| m_1 + e^{i\alpha_2} |U_{e2}^2| m_2 + |U_{e3}^2| m_3 \right|$$



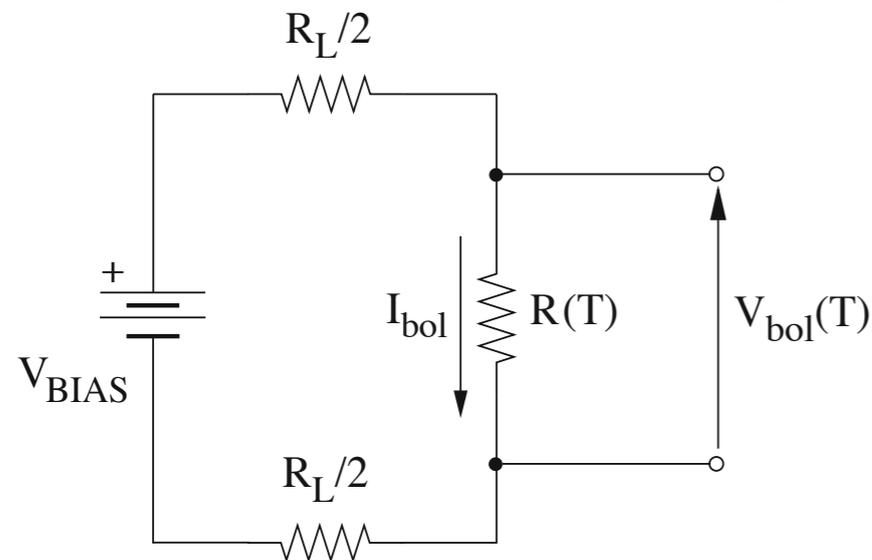
CUORE detector installation



CUORE optimization

Semiconductor thermistor - NTD operation

The thermistor converts thermal pulses into electrical signals, by means of a resistance variation. Si or Ge chips doped by thermal neutrons: Neutron Transmutation Doping (NTD)

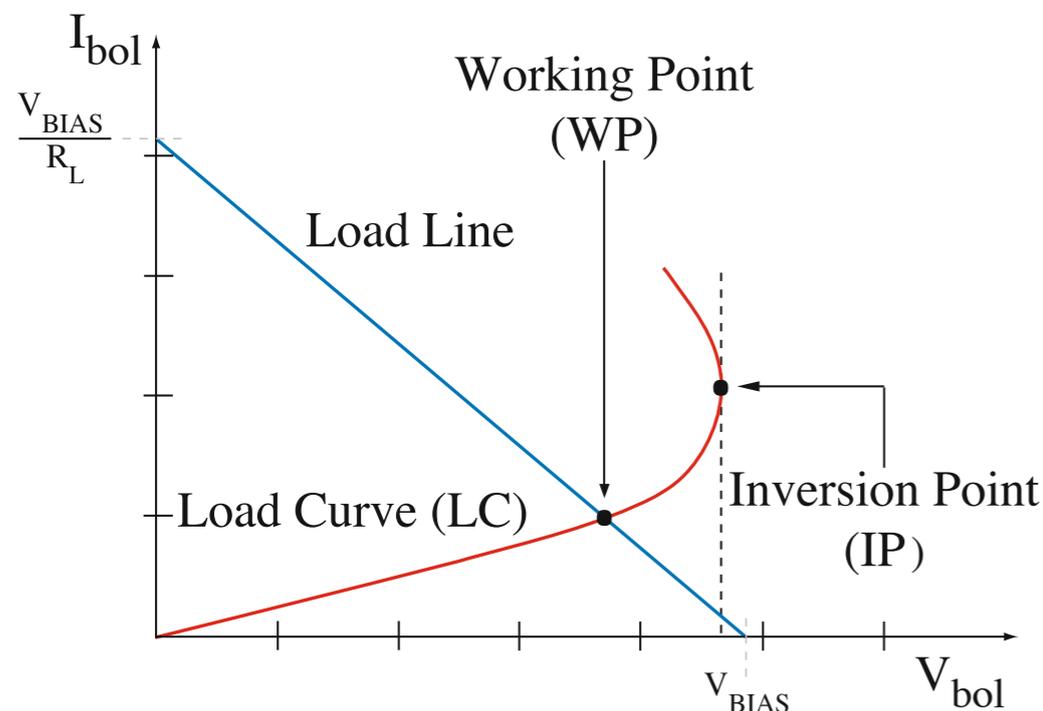


The semiconductor resistivity depends strongly on temperature

$$R(T) = R_0 \exp\left(\frac{T_0}{T}\right)^{1/2}$$

If $R_L \gg R(T)$: I_{bol} constant.

Voltage across the thermistor: $V_{bol} = I_{bol} \cdot R(T)$



Electro-thermal feedback:

Power dissipation $P = I_{bol} \cdot V_{bol}$

that increases the thermistor temperature: $T_s = T_b + \frac{P}{G}$
Decreasing the value of the NTD resistance

Load Curve: I-V relation, deviates from linearity and leads to a non-ohmic behavior

CUORE optimization



Semiconductor thermistor - NTD operation

Sensor response to thermal pulses produced by an energy release in the absorber.

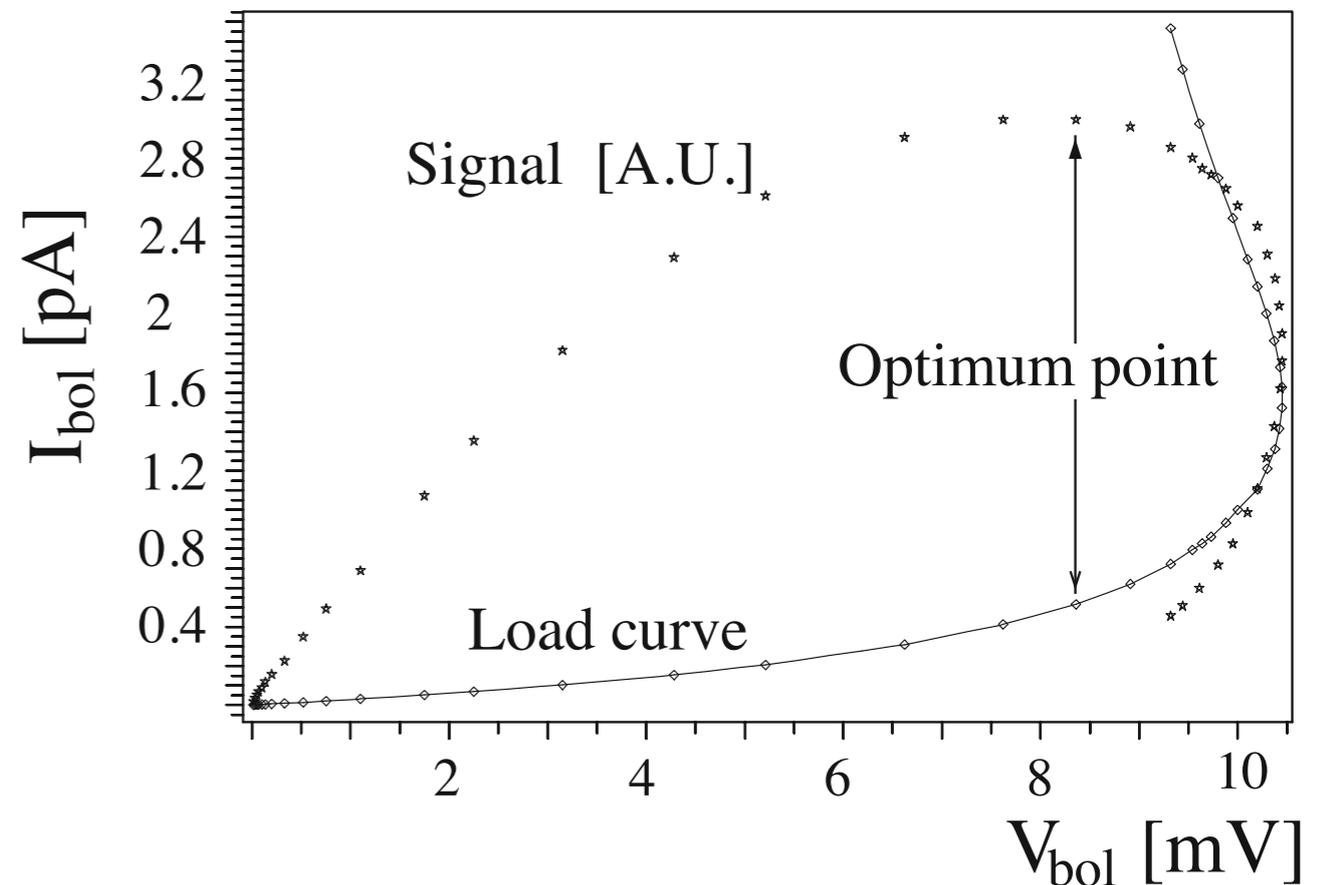
Maximum voltage variation across the thermistor: $\Delta V \propto \frac{\Delta T}{T_s} V_{bol}$

For a given temperature T_b of the heat bath

Optimal working point (V_{BIAS}):

- Optimize the sensor response to particles energy deposition maximizing the signal-to-noise ratio.
- Ensure a linear behavior for small temperature variations

The optimal working point is determined experimentally.



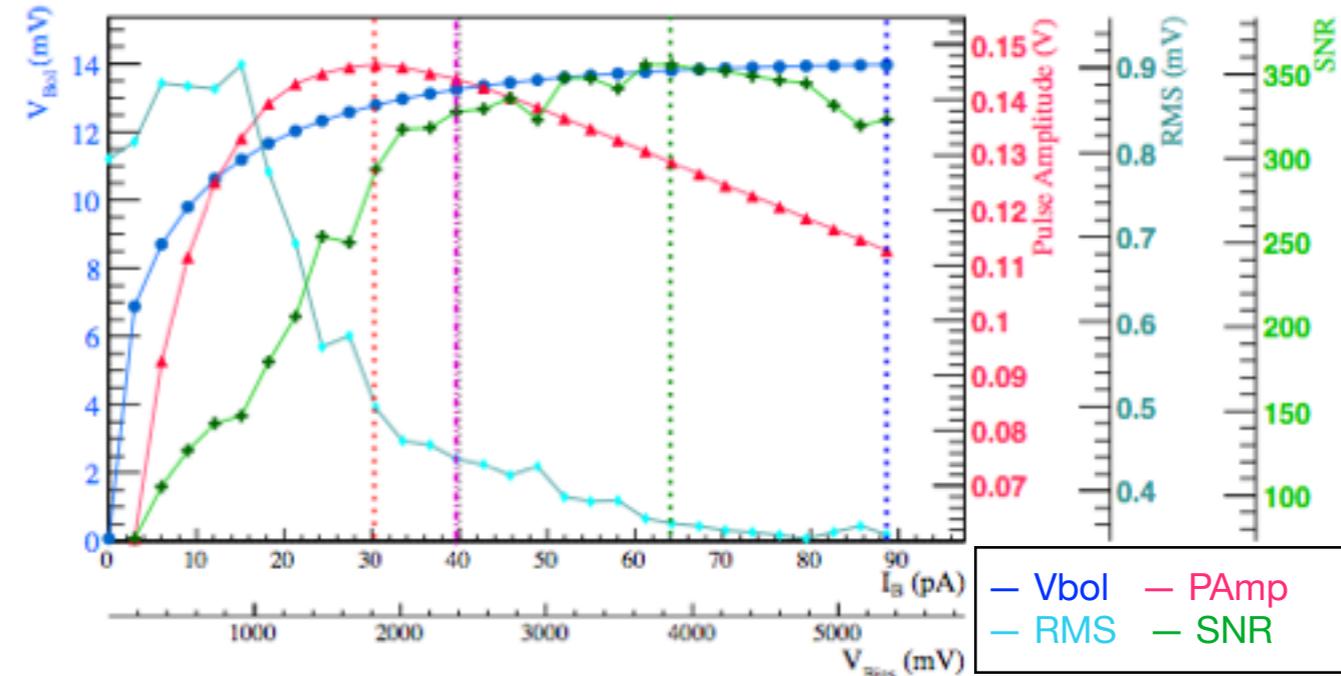
CUORE optimization



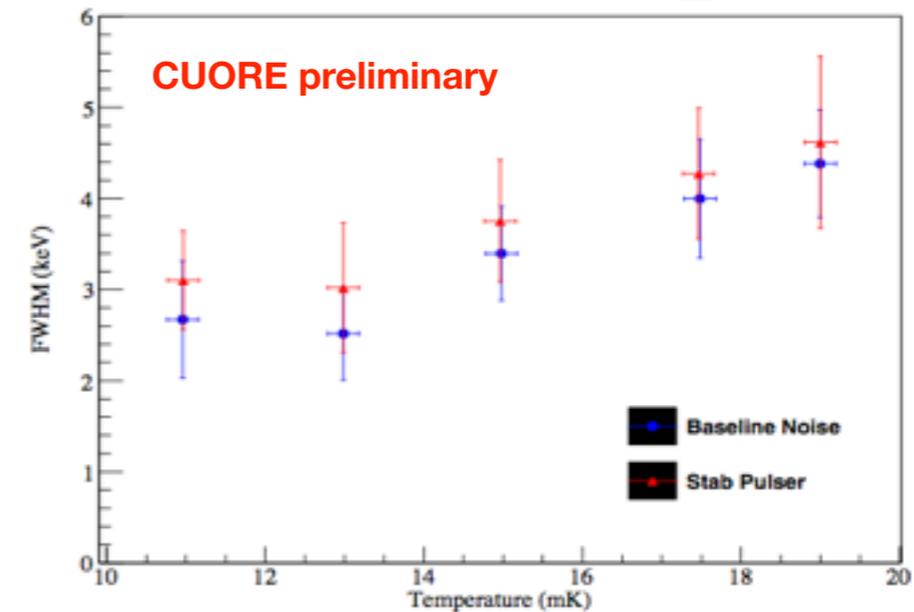
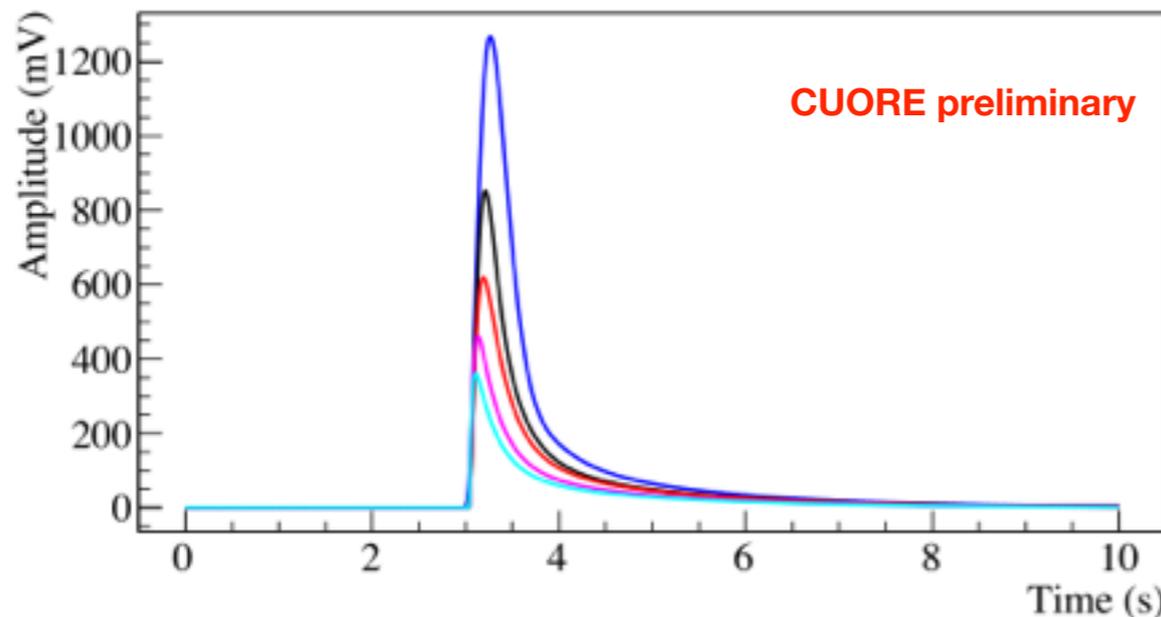
Load Curves, Working Points & Temperature scans

Achieve high quality detector readout with a good signal-to-noise ratio

Dedicated procedures and algorithms in CUORE to automate the load curve measurement and the working point identification at each T_{base} .



- T 11 mK, rise time (10%-90%) 0.148 s, fall time (90%-30%) 0.303 s
- T 13 mK, rise time (10%-90%) 0.102 s, fall time (90%-30%) 0.340 s
- T 15 mK, rise time (10%-90%) 0.090 s, fall time (90%-30%) 0.408 s
- T 17 mK, rise time (10%-90%) 0.055 s, fall time (90%-30%) 0.407 s
- T 19 mK, rise time (10%-90%) 0.039 s, fall time (90%-30%) 0.422 s

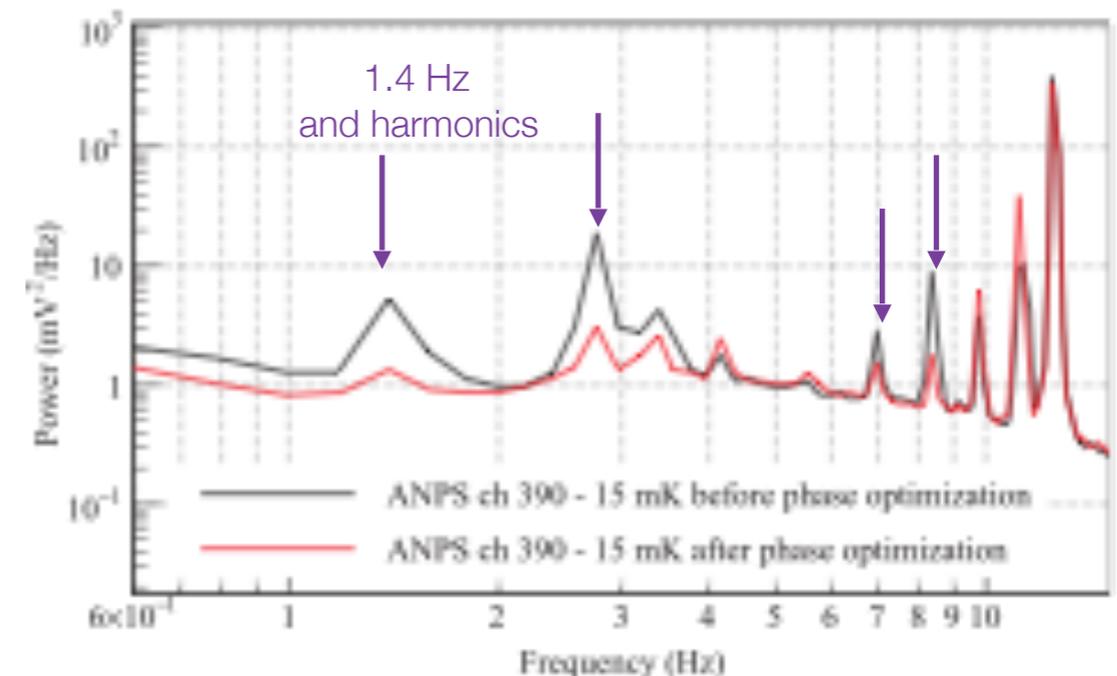
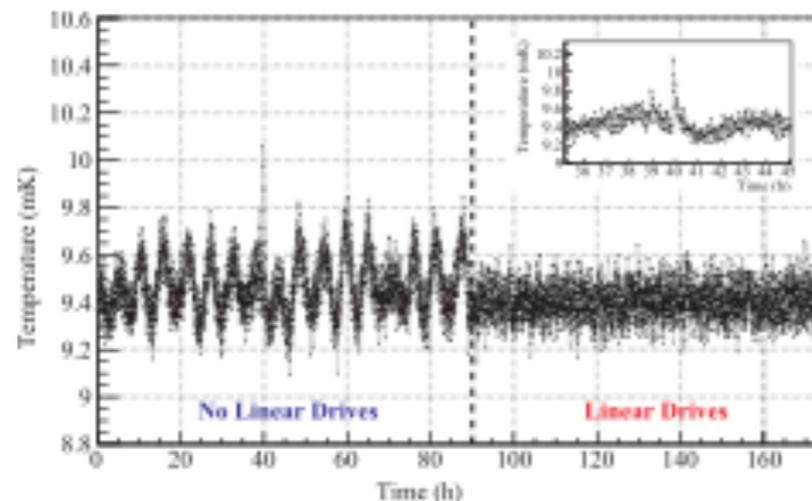
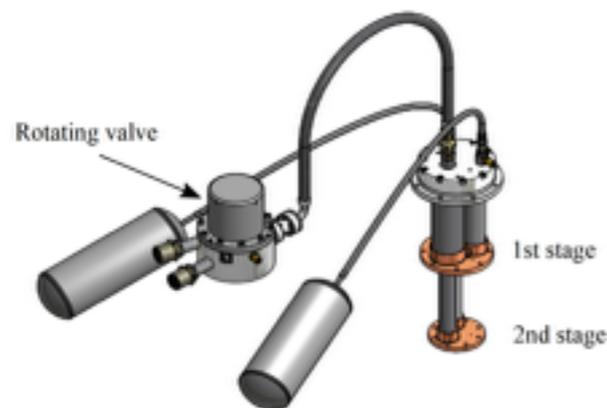


I.Nutini for the CUORE collaboration, J.Low Temp.Phys. 199 (2020) 1-2, 519-528
<https://doi.org/10.1007/s10909-020-02402-9>
 Alfonso K. et al., arXiv:2007.06966 (submitted to JINST)
<https://arxiv.org/abs/2007.06966>

CUORE optimization

Noise reduction

- Pulse Tubes induced vibrations: Pulse Tube active noise cancellation
- Linear Drives: precise control of the PTs motor-head rotation frequency
- Control the relative phases of the pressure oscillations in the Pulse Tubes and set the detectors minimum noise phase configuration



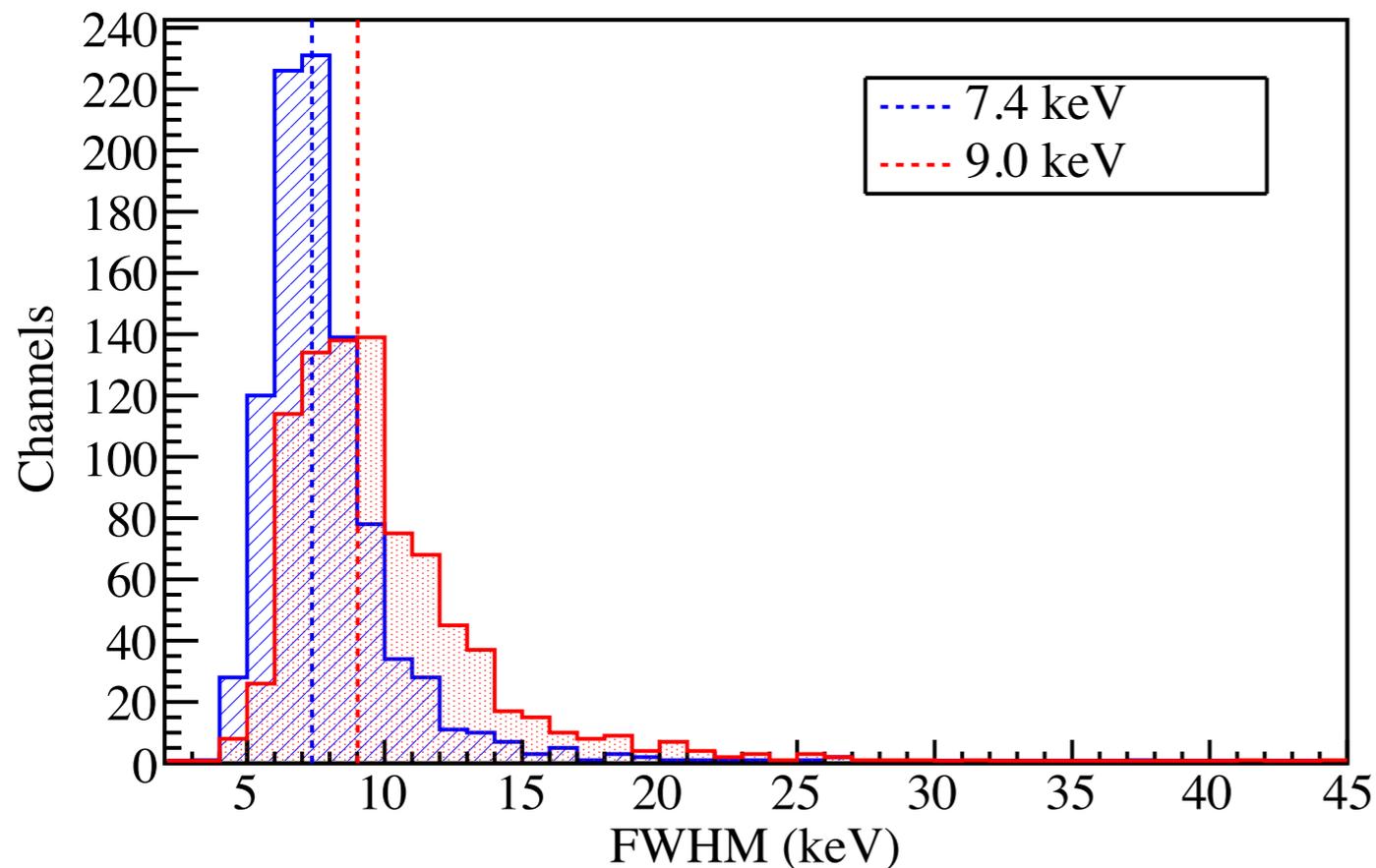
CUORE optimization



Detector performance - Energy resolution

Calibration spectrum

- Energy resolution in calibration runs
@²⁰⁸Tl decay gamma-peak



Energy resolution at 2615 keV in calibration

Dataset 1: 9.0 keV FWHM

Dataset 2: 7.4 keV FWHM

Average: 8.0 keV FWHM - exposure weighted

Improved resolution from **Dataset 1** to **Dataset 2** due to :

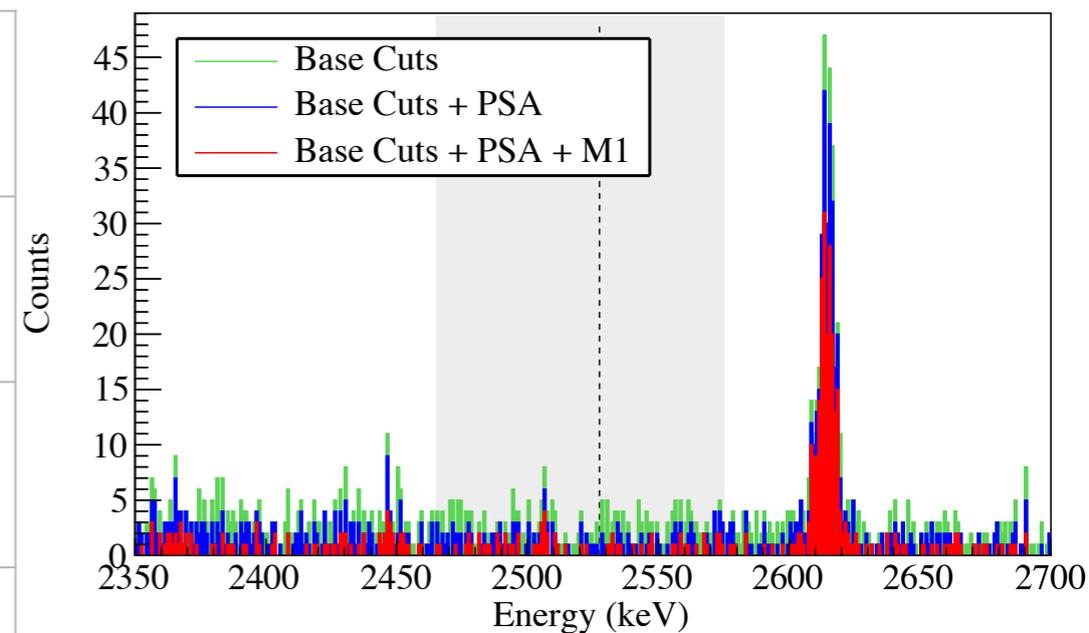
- Investigation and upgrades to the electronics grounding
- Active cancellation of the PT-induced noise
- Optimization of the operating temperature and detector working points
- Software and analysis upgrades

$0\nu\beta\beta$ decay search

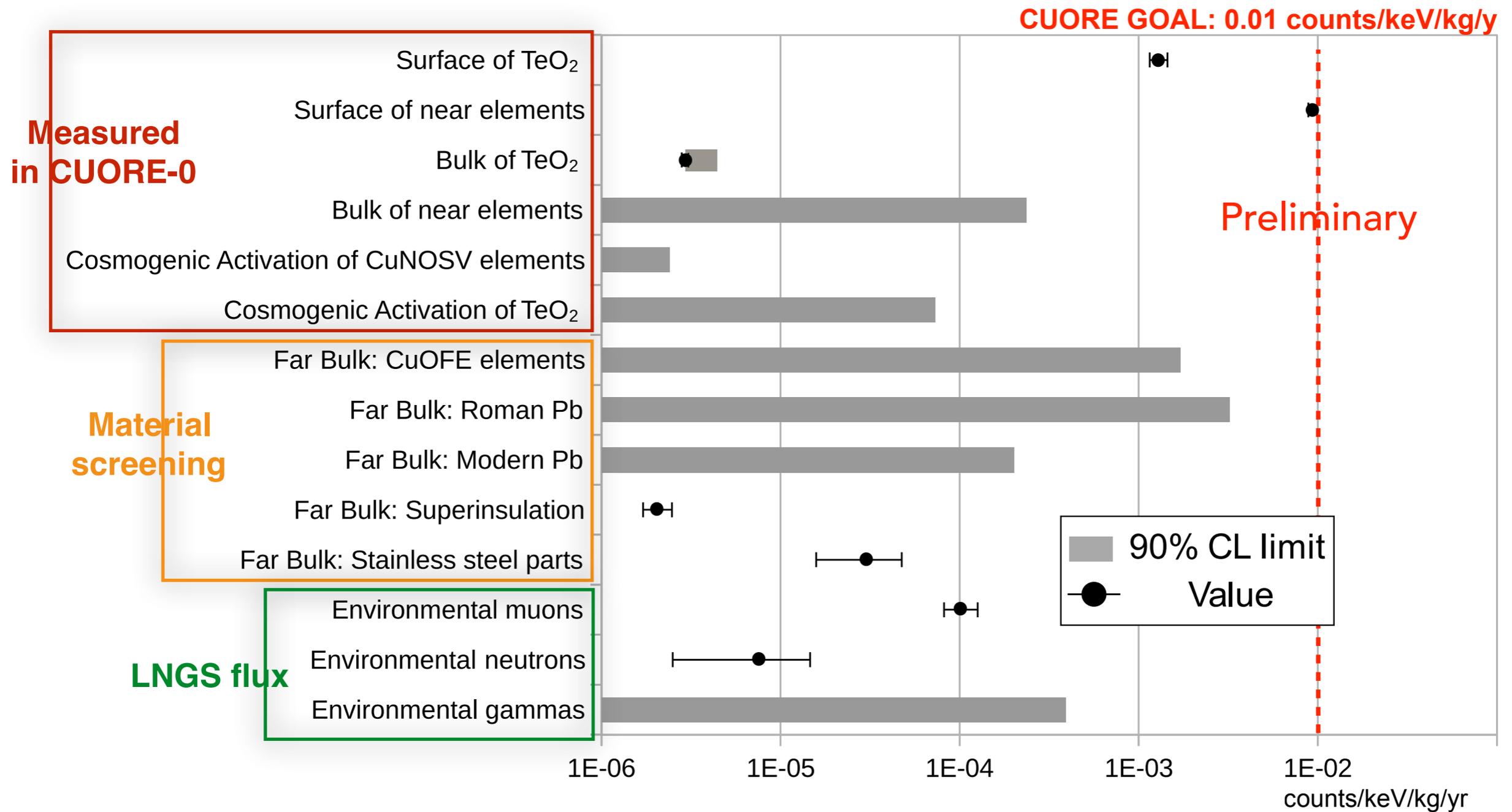
Selection efficiencies

Event selection is performed after discarding periods of low quality data (about 1% of live time)
The $0\nu\beta\beta$ containment efficiency is evaluated from Monte Carlo simulations
All other data-quality efficiencies are evaluated on data.

Base Cuts - Reconstruction Probabilità che un evento sia triggerato e ricostruito all'energia corretta	$95.958 \pm 0.003\%$
Anti-coincidence Probabilità di identificare un evento che coinvolge più cristalli	$98.954 \pm 0.015 \%$
Pulse shape Reiezione di eventi deformati o non fisici	$92.037 \pm 0.108 \%$
Containment Probabilità che un evento $0\nu\beta\beta$ sia contenuto in un singolo cristallo	$88.350 \pm 0.090 \%$



CUORE background budget



CUORE, what's next?

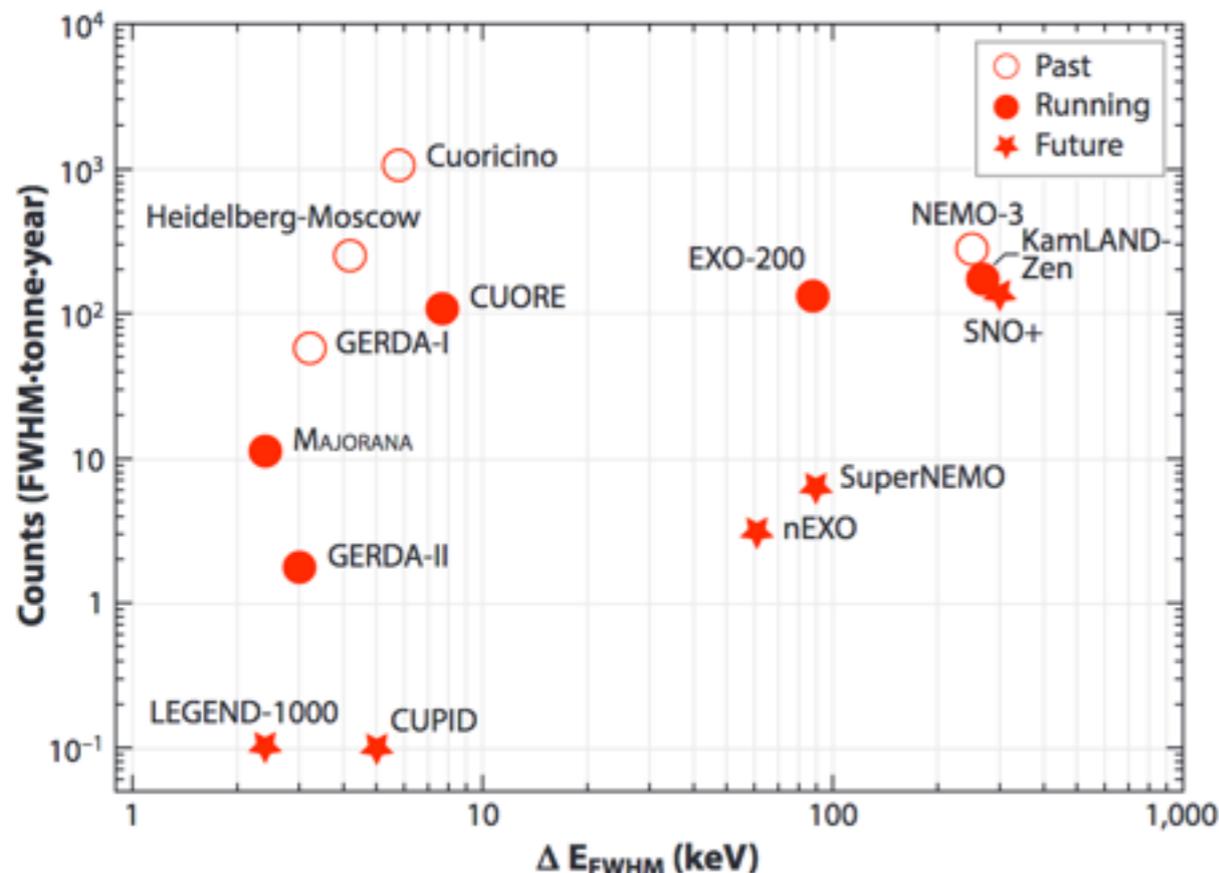
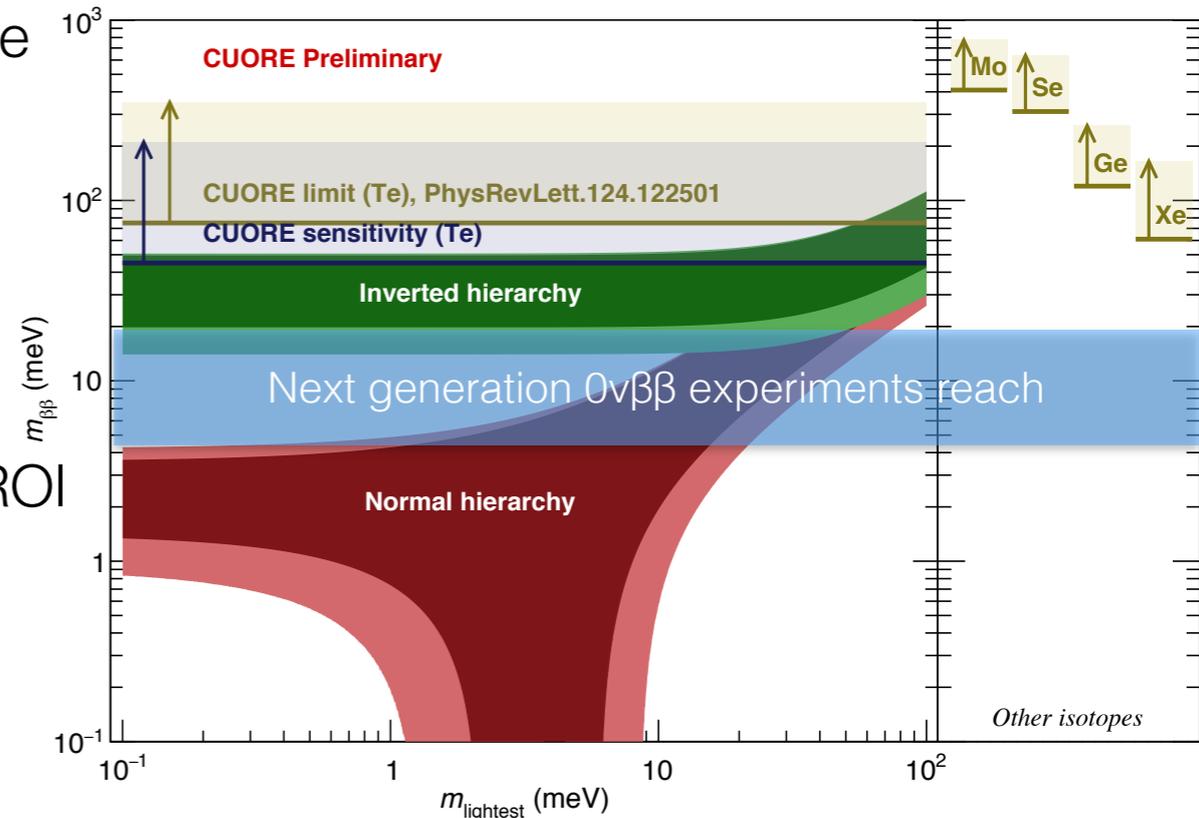


Next generation of $0\nu\beta\beta$ decay experiments seek to be sensitive to the full Inverted Hierarchy region:

Sensitivity $S_{0\nu} \sim 10^{27}$ yr, $m_{\beta\beta} \sim 6 - 20$ meV

To reach these sensitivities:

- Reach the 'zero background' regime: lower the background (and improve energy resolution) in the ROI
- Larger active masses



Dolinski M. et al, Annu. Rev. Nucl. Part. Sci. 2019.69:219-251
<https://www.annualreviews.org/doi/pdf/10.1146/annurev-nucl-101918-023407>

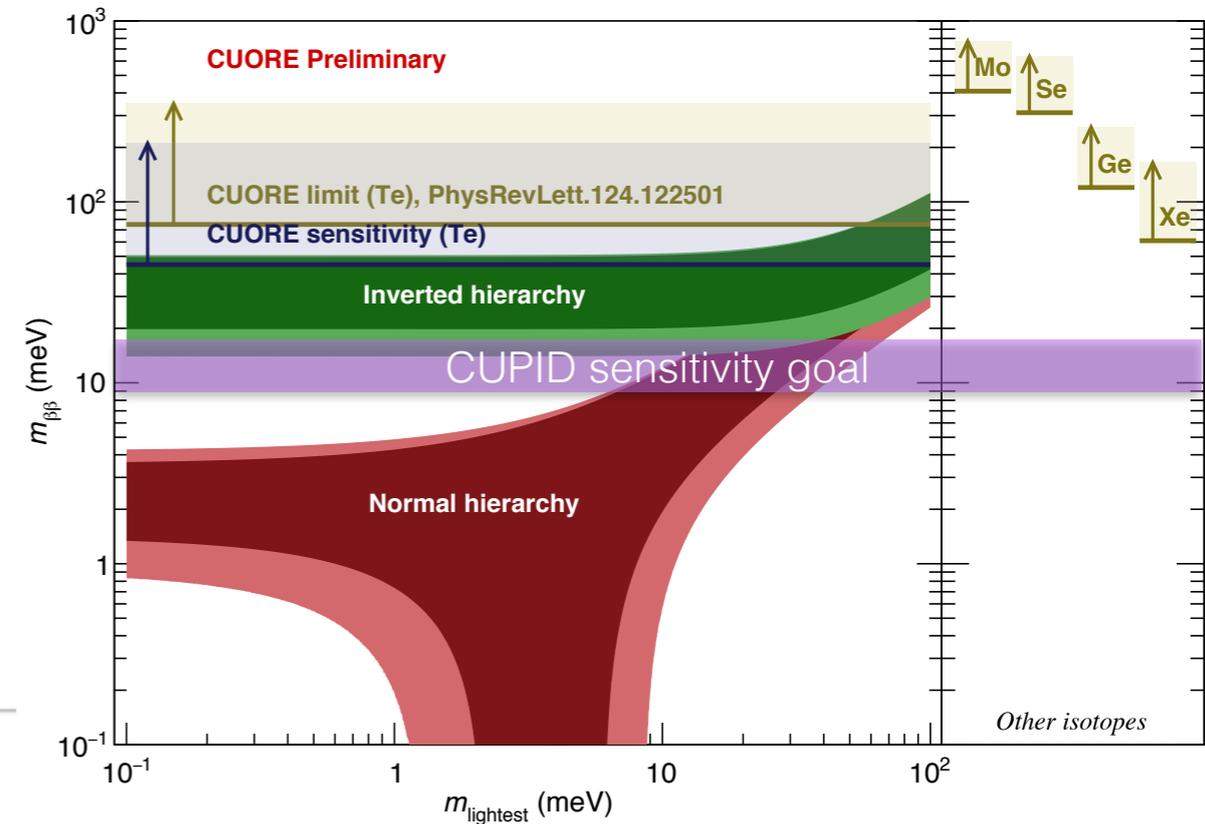
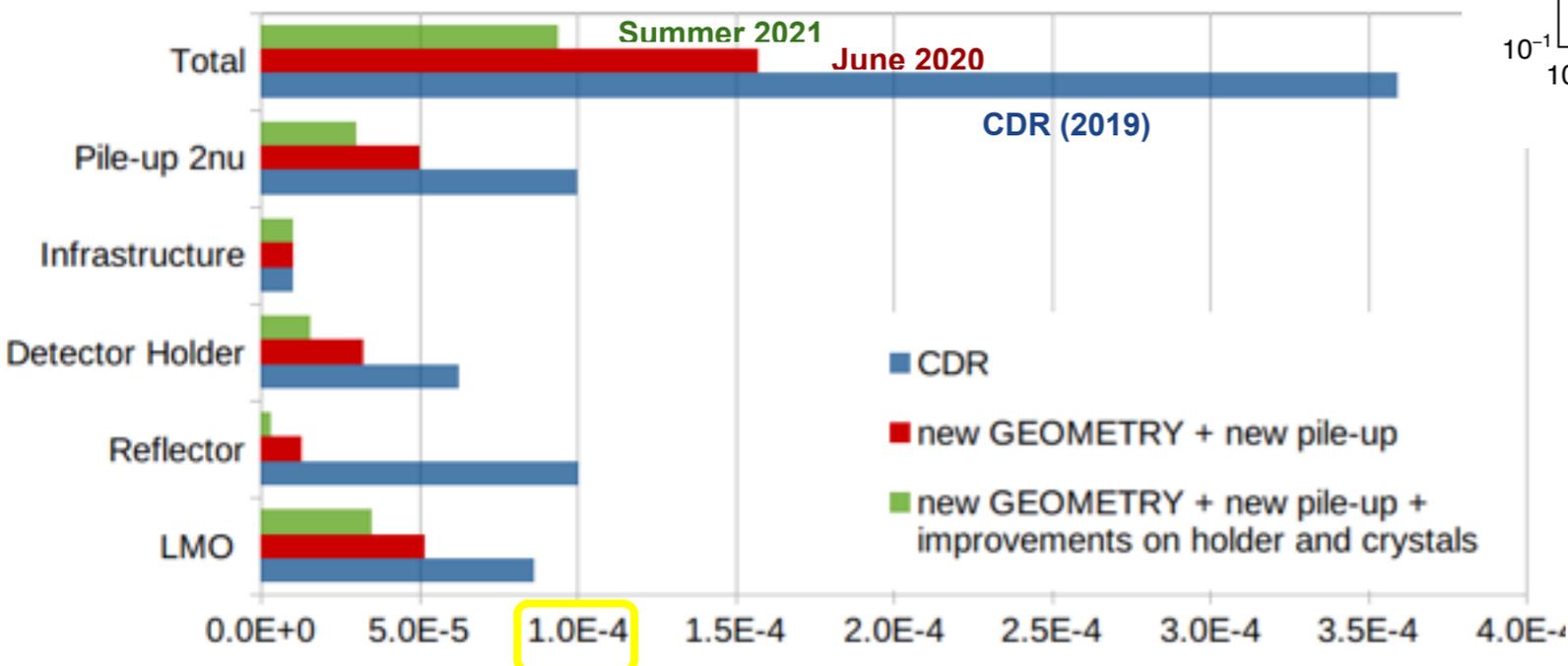
CUORE, what's next? CUPID



CUPID: 1 tonne of scintillating LiMoO₄ detectors

- Energy resolution goal: ~5 keV FWHM at $Q_{\beta\beta}$
- Background goal: $B \sim 10^{-4}$ c/(keV·kg·yr) nella ROI

CUPID background budget



^{100}Mo $2\nu\beta\beta$ half-life $\sim 7 \times 10^{18}$ yr
 rate ~ 3 mHz/crystal

CUPID pre-CDR - arXiv:1907.09376